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STATIC AND DYNAMIC CREEP PROPERTIES OF LAMINATED PLASTICS FOR VARIOUS TYPES OF STRESS

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SUMMARY

Creep tests of five laminated plastics were made in this investigation to determine the relative creep properties of these materials when subjected to various types of static and dynamic stresses. Creep deformations were measured to determine the variation of these deformations with stress. For each type of test, the stress values investigated covered the stress range from zero stress to the ultimate strength of the material. Static creep tests were made for tension, bending and torsion, and the creep behavior was studied for fluctuating axial loads superimposed on static tensile loads. In general, the various kinds of creep tests show that the creep deformation resistance varies with the ultimate tensile strengths of the laminates except for the torsion creep tests of square cross sections. Attempts were made to interpret the creep test results for the purpose of obtaining a stress-creep rate relation. The log-log, log and hyperbolic sine methods of interpretation were used. The agreement between these methods of interpretation and the test results was not satisfactory so that the results of these interpretations are not included in this report.

In selecting the loads to be used for the creep tests it was first necessary to make control static tests in tension, compression, bending, and torsion. For these simple stress tests values of yield strength, ultimate strength, stiffness and ductility were determined. It was found that the mechanical properties of a laminate for one type of simple stress are not always indicative of what the properties will be for another kind of stress. For example, it was found that the cotton base laminate with almost the lowest tensile ultimate strength has the highest torsional ultimate strength.

An auxiliary program of tests was made to determine the influence of repeated stressing, up to 100 cycles, on the strength, stiffness, and ductility in tension and compression. Three types of repeated stress tests were made - repeated tension followed by a test to rupture in tension, repeated compression followed by a test to rupture in

compression, and repeated tension followed by a test to rupture in compression. The repeated stresses were up to two-thirds of the ultimate strengths for each test. From the test results obtained no general conclusion can be made on the influence of prestressing on the mechanical properties.

INTRODUCTION

When materials such as laminated plastics are subjected to loads, the stresses produced are accompanied by deformations which increase in magnitude with time. These deformations, called creep deformations, are in addition to the elastic deformations and may occur at low stress values. For some materials subjected to stresses below the yield stress, creep deformations occur only at elevated temperatures. An important application of steel at elevated temperature is the steam turbine for which a design stress must be selected based on a permissible creep deformation that allows adequate clearance between the moving parts of the turbine. The design stresses in aircraft parts using laminated plastics must also be selected so that creep deformations will not distort the members to an undesirable extent.

The presence of creep in materials subjected to stress influences the type of stress distribution and the maximum stress value for all types of stress except simple tension and compression. For example, creep tests in bending show that the maximum stress calculated using methods developed in the mechanics of creep (reference 1) may in some cases be about two-thirds of the maximum stress obtained by the usual elastic theory. It seems desirable therefore to include in a complete investigation of creep, both a determination and an interpretation of experimental data for various types of stress. It may then be possible to apply these data to the formulation of a mechanics of creep applicable to the particular material investigated.

In the past, most creep tests on plastics have been made for simple tension (reference 2). Although tension-creep tests may give a comparison of the creep properties for various plastics, the fact remains that other kinds of stresses are produced in aircraft parts. For this reason, the present investigation includes a study of the creep-stress relations not only for simple tension but also for static torsion, static bending, and static tension combined with fluctuating axial stress. Tests were also made for dynamic torsion combined with static tension but are not reported since unreasonable test results were obtained. Special equipment was built for the creep tests and in most cases creep deformations were observed for stress values covering the complete range of stresses to the ultimate strength.

Control tests were made on the five laminates in tension, compression, torsion and bending to determine the mechanical properties of yield strength, ultimate strength, stiffness and ductility. The purpose of making these tests was threefold - (1) to select stress values to be used for the creep tests, (2) to compare properties with those when repeated stressing was used, and (3) to provide a more complete study of the physical properties.

At the suggestion of the Air Materiel Command, Army Air Forces, tests were also conducted to determine the influence of repeated stressing in tension and compression on the mechanical properties of the various laminated plastics.

This investigation was conducted by the School of Engineering of The Pennsylvania State College under the sponsorship and with the financial assistance of the National Advisory Committe for Aeronautics. Most of the tests were conducted in the creep laboratory of the Department of Engineering Mechanics. Messrs. W. C. Kish and H. A. Albala were, respectively, full-time and part-time research assistants for this project. Special equipment and specimens were made by Messrs. S. S. Eckley, E. Grove, and H. Johnson. Professor K. J. DeJuhasz of the Engineering Experiment Station designed special tension and compression strain gages and grips for the tension tests. Professor F. G. Hechler gave valuable advice on several problems including the control of humidity for the tests. Dr. G. M. Kline, Chief of the Organic Plastics Section of the Bureau of Standards, gave technical assistance on various phases of the project. The administrative direction given by National Advisory Committe for Aeronautics and the College of Engineering and the technical assistance given by the foregoing individuals in making possible this investigation was greatly appreciated.

SYMBOLS

A cross-sectional area of specimen, square inches

b width of cross section for bending specimens, inches

C creep rate for all creep tests

C_b creep rate in bending

C_s creep rate in torsion, degrees per inch per hour

C_t creep rate in tension, inches per inch per hour

D diamter of round torsion specimen, inches

d depth of cross section for bending specimen, inches

E_b modulus of elasticity in bending, pounds per square inch

E_c modulus of elasticity in compression, pounds per square inch

E_s modulus of elasticity in shear, pounds per square inch

E_t modulus of elasticity in tension, pounds per square inch

e amplitude of motion of eccentric weights for dynamic creep tests, inches

e_c strain, inches per inch at rupture in compression

e_t strain, inches per inch at rupture in tension

e_{ct} creep strain, inches per inch in tension

F_s total axial tension dynamic force, pounds

L gage length or span length, inches

M bending moment, inch-pounds

M_e mass of rotating eccentric weights, pounds per second per second per inch

M_o total axial mass applied in dynamic tests, pounds per second per second per inch

N number of stress repetitions in repeated stress tests

P_b load in static bending test at rupture, pounds

R_t ratio of static tension to maximum tensile stress in dynamic tension tests

S general symbol for stress for all tests, pounds per square inch

S_B ultimate strength (modulus of rupture) for bending, pounds per square inch

S_C ultimate strength for compression, pounds per square inch

S_S ultimate strength (modulus of rupture) for torsion, pounds per square inch

S_T ultimate strength for tension, pounds per square inch

S_{yc} yield strength for compression, pounds per square inch

S_{yt} yield strength for tension, pounds per square inch

S_m static tensile stress in dynamic creep tests, pounds per square inch

S_s shear stress for torsion creep tests, pounds per square inch

S_t tension stress for tension creep tests, pounds per square inch

T_S static twisting moment at rupture, inch-pounds

W_o static tensile load applied in dynamic tension tests, pounds

y_b deflection in static bending tests at rupture, inches

θ angle of twist in static torsion tests, degrees

ω frequency of forced vibration in dynamic creep tests, radians per second

φ phase angle, degrees

DESCRIPTION OF MATERIALS

Five laminated plastics were selected for investigation:

1. Glass fabric laminate with polymerizing type resin (G)
2. High strength paper base plastic (P)
3. High strength rayon laminate with phenolic resin (R)
4. Grade C phenolic resin laminate (C)
5. Cotton fabric laminate as used in Grade C but molded with low pressure (CL)

For convenience in referring to these plastics, the letter given in the brackets above will be used. Information regarding the manufacture of the laminates as supplied by the manufacturer is given in table 1. All the materials tested, except the glass laminate (G), were cross-laminated.

Table 1 gives values of thickness and density of the laminates and information regarding the resin, reinforcement, and molding conditions.

TEST PROCEDURE

(a) Static Tests

Standard tension, compression, and bending tests were made as outlined in the Federal Specifications (reference 3). The dimensions complied with the specified values except that the bending specimens were tested edgewise since it was necessary to test the creep bending specimens edgewise. Static torsion tests for both square and round specimens were made in order to determine the loads to be used for the torsion creep tests. For all tests, the specimens were held at 50 percent ± 2 percent relative humidity and the temperature was maintained at $77^{\circ} \pm 5^{\circ}$ F during the test and 48 hours previous to testing. The tension and compression tests were made in a 50,000-pound Universal Olsen machine (fig. 1). An enclosure was constructed around the testing machine as shown so that air at 50 percent relative humidity could be maintained by a pipe connection from the creep laboratory. This provision for controlled humidity was particularly necessary for the repeated tension and compression tests since some of these latter tests required several hours for completion.

For the <u>tension tests</u>, special grips were constructed with spherical seats to ensure axially applied loads (fig. 2), and the deformations were measured by a specially designed, averaging type strain gage (fig. 2) reading to 5×10^{-5} inch per dial division. The gage length used was 2 inches and the specimens were about 3/8 by 1/2 inch in cross-section. Load-strain readings were taken to rupture for at least two specimens of each laminate. When a large difference in the results of two tests was obtained, more than two tests were made.

For the <u>compression tests</u>, spherical seats and a specially designed, averaging type strain gage (fig. 3) were used. The accuracy of the strain gage used meets the Federal specification requirement by reading to 4.89×10^{-4} inch strain per gage division. The gage length used was 1 inch and the cross-sectional dimensions of the specimens were about 1/2 by 1/2 inch. Load-strain readings were recorded to rupture for at least two specimens as for the tension tests.

For the <u>bending tests</u>, specimens about 1/2 inch wide by $1\frac{1}{8}$ inches deep were loaded at midspan. The specimens were loaded in the edgewise position since the creep test specimens were so loaded. The span-depth ratio was about 7. Deflections at the midspan were measured with a dial gage reading to 0.001 inch. Readings of load and deflections were recorded to rupture for at least three specimens of each material.

Static torsion tests were made so that torsion load values could be selected for the torsion creep tests. The tests were made in the torsion creep machine shown in figure 9. Specimens of both round and square cross sections were tested since creep tests using both kinds of cross sections were made. The round specimens were about 1/2 inch in diameter and the square specimens were about 1/2 by 1/2 inch. The angle of twist was measured to 0.1° for a gage length of 6 inches for both types of specimens. Load-angle of twist readings were taken to rupture for at least three specimens of each laminate.

For the tension, compression and bending tests, the readings were taken "on the run" and the rate of strain used was within the value specified by the Federal Specifications (reference 3). The scale load interval on the testing machines was 5 pounds and the testing machine was calibrated.

(b) Repeated Stress Tests

Standard size tension and compression specimens were used to study the influence of repeated stresses on the mechanical properties of the laminates in tension and compression. The types of repeated tests made were: repeated tensile stressing, followed by testing to rupture in tension, repeated compressive stressing followed by testing to rupture in compression, and repeated tensile stressing followed by testing to rupture in compression. In all tests, the number of stress repetitions (N) was 100 and the magnitude of the maximum stress during these repetitions of stress was two-thirds the ultimate stress. Some tests were made using smaller numbers of stress cycles and lower maximum stresses but the results of these tests are not included since there was negligible effect on the stress-strain relations. Only two tests were made for each type of test and material when the ultimate strength values checked, but creep tests were run in cases of discrepancy. For the tests in which repeated stressing in tension was followed by a compression test, a specimen about 2 inches long was cut from the middle part of the tension specimen to permit testing the material in compression. For the repeated tension tests, load-strain readings were obtained on the first reduction of load from two-thirds the ultimate stress to zero stress so that hysteresis cycles could be plotted.

(c) Creep Tests

All creep tests were made in a room in which the temperature was $77^\circ \pm 5^\circ$ F and the relative humidity 50 percent $\pm$ 2 percent. The humidity was maintained constant by means of both a humidifier and dehumidifier having automatic controls. Static tension, static bending, static torsion, and dynamic creep tests were made to determine the stress-creep deformation relations for these various types of stress.

The static tension creep tests were made using the two-lever type tension creep testing machines shown in figures 4 and 5. By means of the lever loading system used, a constant stress was maintained on a specimen during a test. The creep tension specimens had the same dimensions as the standard tension specimens except that a longer straight section was provided which gave a gage length of 10 inches. This increased gage length ensured increased accuracy in the creep strain readings. The creep strains were measured by means of a strain gage using micrometer microscopes as shown in figure 6. Target points on the specimens were provided by using black India ink dots on a white painted background. The total creep strains were measured to 0.00002 inch.

Static bending creep tests were made using specimens 1/2 inch wide by 1 1/8 inches deep. The tests were conducted in the machine shown in figure 7. A single creep bending unit is shown in figure 8, illustrating how the specimen is subjected to a pure bending moment free from transverse shear stresses. Creep deflections were measured over a 2-inch gage length by means of dial gages reading to 0.0001 inch.

Static torsion creep tests were made on laminates R, P and G, using both round (1/2 in. diameter) and square (1/2 by 1/2 in.) specimens. Although the round cross section is the type usually used in materials testing, the influence of the binding material in laminates is different in square and round cross sections. For this reason both types of cross sections were used. The torsion creep tests were made, using the four-unit machine in figure 9. The loading arrangement consists of a dead weight applied to a pulley which produces pure torque on the specimen by means of adequate bearing supports (fig. 10). The angle of twist was measured over a 6-inch gage length by means of a twist meter with a vernier reading to 0.1°.

Dynamic tension creep tests were made using a hypocyclic oscillator type dynamic machine as shown in figure 11 and described in reference 4. In these tests, a static tensile load was applied to the specimen by weights (fig. 11) and a superimposed fluctuating axial load was produced on the specimen by the oscillator. The creep elongations were measured for a 7-inch gage length using micrometer microscopes as for the static tension creep tests. The capacity of the oscillator made it necessary to use specimens of small cross sections about 0.25 by 0.10 inch. During a test, heating of the specimen was prevented by the use of circulating air produced by a fan.

In all creep tests, initial strain readings of the creep measuring instruments were recorded before the specimen was loaded. After loading the specimens, the initial deformation was recorded and readings of the creep deformations were noted at selected intervals of time throughout the life of the test. The static tension tests covered a period of 1400 hours, the static bending and torsion 1000 hours, and the dynamic tension 200 hours. It was necessary to use the shorter period of time of 200 hours for the dynamic tension tests since only one such test could be run at one time.

Creep tests also were made on specimens subjected to fluctuating torsion superimposed on static tension. The results of these tests were erratic, and unreasonable values for the dynamic shear stress were obtained based on the measured angles of twist. It is probable that the errors introduced were in the measured angles of twist resulting from the use of specimens with small cross sections. The results of these dynamic torsion creep tests are omitted from this report since they are unreliable.

TEST RESULTS

(a) Static Tests

Load-deformation relations for the tension, compression, bending, and torsion tests are shown in figures 12, 13, 14, 15, and 16, respectively. From these graphs, and where it was possible, the following mechanical properties were determined: (1) the yield strength defined by 0.2 percent offset strain, (2) the ultimate strength or modulus of rupture, (3) the stiffness as defined by the secant modulus of elasticity and (4) the ductility as defined by the deformation at rupture.

The values of the properties for tension and compression, obtained from figures 12 and 13, are listed in tables 2 and 3. The secant modulus values given are based on the slope of the line between the points of zero and 5000 pounds per square inch stress values.

The values of the mechanical properties for bending, as obtained from figure 14, are given in table 4. In table 4, the ultimate strength (modulus of rupture) and stiffness were calculated on the basis that the material obeys Hooke's Law in tension and compression and that the material is homogeneous and elastic. That is, the ultimate strength (S_B) and stiffness (E_b) are respectively

$$S_B = \frac{3P_bL}{2bd^2} \qquad (1)$$

$$E_b = \frac{P_b' L^3}{4 y_b b d^3} \tag{2}$$

where

P_b load at rupture

P_b' load corresponding to a stress S_b equal to 5000 psi

L span length

b width of specimen

d depth of specimen

y_b deflection corresponding to load P_b'

The ductility in bending is given in table 4 in terms of the center deflection at rupture.

The mechanical properties in torsion as determined from figures 15 and 16 for both round and square specimens are listed in tables 5 and 6. Assuming for comparative purposes that the ultimate strength (modulus of rupture) can be determined by the theory of elasticity (reference 5), the ultimate strength (S_s) for the square and round cross sections are respectively

$$S_s = \frac{T_s}{0.208 t^3} \tag{3}$$

$$S_s = \frac{5.08 T_s}{D^3} \tag{4}$$

where

T_s twisting moment at rupture

t cross-sectional dimensions of the square specimens

D diameter of the round specimens

The stiffness (E_s) is determined in tables 5 and 6 based on the secant modulus for a stress of 2500 psi. Assuming the theory of elasticity, the values for the stiffness for the square and round cross sections are respectively

$$E_s = \frac{407 \, L T_s'}{t^4 \, \theta_s} \tag{5}$$

$$E_s = \frac{584 \, L T_s'}{D^4 \, \theta_s} \tag{6}$$

where

T_s' twisting moment corresponding to a stress equal to 2500 psi using equation (3) or (4)

θ_s angle of twist in degrees for torque (T_s')

L gage length

The ductility values in tables 5 and 6 are the angles of twist at rupture for a 6-inch gage length.

A comparison of the mechanical properties of the five laminates is given in table 7 based on 100 percent for the highest value of the mechanical property considered.

(b) Repeated Stress Tests

The load-strain diagrams for the repeated stress tests are given in figures 12, 13, and 17. In figures 12 and 13, the load-strain diagrams are given. These diagrams are designated for N = 100, where N is the number of stress applications to two-thirds the ultimate stress. The values of the mechanical properties of yield strength, ultimate strength, stiffness, and ductility as obtained from the load-strain diagrams are given in tables 8, 9, and 10. The values of these properties were determined in the same manner as for the static tests. Using values from tables 2, 3, 8, 9, and 10, the percent change in properties produced by repeated stress was calculated and listed in table 11. Hysteresis cycles in tension were obtained as shown in figure 18. The area bounded by the load-strain lines is proportional to the energy dissipated per cycle of stress and is of practical interest since this energy determines the damping properties of the material. The values of these energies, as obtained from figure 18 and expressed in inch-pounds per cubic inch are given in table 12.

(c) Creep Tests

The static tension creep-time relations are plotted in figures 19 to 23 for the five materials tested. The strains per inch of gage length were calculated from the micrometer microscope readings, and the values plotted included both the elastic and creep strains in compliance with the usual practice. In the creep-time plots, the tests that do not cover the entire testing time as shown by a solid or dotted line indicate that the specimen ruptured.

The static bending creep-time diagrams plotted in figures 24 to 28 are shown in terms of total creep deflection for a 2-inch gage length since the creep deflection was measured for a 2-inch gage length and the deflection is not proportional to the gage length.

The static torsion creep-time graphs are given in figures 29 to 35 for materials R, P, and G as requested. These relations are given for both round and square specimens in terms of creep angle of twist per inch gage length versus time in hours. The stresses shown for each creep time graph in the bending and torsion creep tests were computed using equations (1), (3), and (4).

For the dynamic tension creep tests, the unit creep strain-time graphs are given in figures 36 to 40 for various values of the mean or static stress (S_m) applied. To determine the value of the dynamic axial force, the following equation obtained from reference 4 was used,

$$F_s = \frac{M_e e \, \omega_o^2 \cos \varphi}{1 - \dfrac{M_o L}{E_t A} \omega_o^2} \qquad (7)$$

where

F_s total axial dynamic force

M_e mass of the rotating eccentric weights

e amplitude of motion of the eccentric weights when the oscillator is stationary

ω_o frequency of the forced vibration

φ phase angle

E_t static modulus of elasticity in tension

M_o total mass applied including eccentric weights (W_o/g)

L over-all length of specimen

A cross-sectional area of specimen

The maximum tensile stress applied by the static and dynamic forces is then

$$S_t' = \frac{W_o + F_s}{A} \tag{8}$$

and the mean static stress is

$$S_m = \frac{W_o}{A} \tag{9}$$

The values of the maximum and mean stresses S_t' and S_m and the stress ratios $R_t = S_m/S_t'$ are given in table 17 for each test. For comparison of the dynamic creep properties of the five laminates it would have been desirable to maintain the stress ratio R_t constant for all tests. Because of the number of variables influencing the dynamic force value F_s (see equation (7)) it was not possible to fix the value of the ratio R_t. However, except for the G material, the values of R_t varied only a slight amount from the average value of 0.64. For this reason the creep data for the laminates can be compared.

The types of fractures produced in the static and creep tests are illustrated in figures 41 to 47.

ANALYSIS AND DISCUSSION

An examination of the values of the mechanical properties in tension, compression, bending, and torsion, as given in tables 2 to 7, shows that the properties of a particular laminate are not equally as good for all types of stress. For example, table 7 shows that the G laminate has the greatest tensile strength and the CL material the least; whereas for the CL material, the ductility is greatest and for the G laminate it is least. Also, for both compression and bending, although the G material has the greatest strength, the CL material has the best ductility. In torsion, table 7 shows that the C laminate has the greatest ultimate strength while the R material has the best ductility. Apparently the choice of laminate depends upon the particular type of member to be designed, the type of stress in the member, and the strength and ductility requirements that are considered adequate. It should be noted that the determination of the mechanical properties was a secondary purpose in this investigation, and an exact comparison with precise test results was not expected.

The influence of repeated stressing of 100 cycles on the tension and compression properties is shown in table 11. Positive percentage values given represent an improvement in the particular mechanical property while a negative value represents a decrease in the magnitude of the property. From a comparison of values in table 11 the following analysis can be made:

1. For tension stressing followed by a tension test.- The influence on the tensile strength was negligible for all laminates and there was a decrease of about 25 percent in ductility and stiffness for the CL, C, and R laminates, and an increase in yield strength for these materials.

2. For compression stressing followed by a compression test.- The influence on the compressive strength was negligible for all laminates and there was an increase in yield strength for the C, R, and P laminates. The stiffness of the CL, R, and P materials decreased and the ductility decreased for all laminates.

3. For tension stressing followed by a compression test.- For the CL, C, and G laminates there was a decrease in compressive strength and ductility, while for the P material there was a slight increase. The yield strength of the CL, C, and R materials increased and the stiffness of these laminates decreased. It should be noted that in some cases the percentage differences given in table 11 are within the difference obtained from two standard tests. Limited time prevented a more thorough study of the influence of repeated stress. That is, it would be desirable to consider intermediate values of number of stress cycles and other ranges of stress.

The values of the energy dissipated per cycle during stressing in tension to two-thirds the ultimate stress are given in table 12. The values listed show that the R and P materials have the best damping properties. The G material has the poorest damping value, having only about 17 percent of the value for the R laminate.

Values of the creep deformations for the duration of the tests, as obtained from figures 19 to 40, are listed in the last column of tables 13 to 17. Table 18 gives the creep deformations for the various laminates corresponding to particular stress values. The creep deformations given in table 18 were obtained by plotting values of the creep versus stress as given in tables 13 to 17, and represent approximate values only. The relative creep characteristics for the various materials under tensile, bending, torsion, and dynamic tension are indicated also approximately by the curves given in figures 48 to 52. An examination of the creep-stress relations for various types of stress shows that the creep resistance varies with the ultimate tensile strength of the material except for the torsion creep tests on square specimens. That is, the material creep rating is in the following order: G, P, R, C, and CL, with the G laminate having the highest resistance to creep. The magnitudes of the creep deformations have a wide range for the five laminates. For example, the creep deformation under a static tensile stress of 6000 psi, for the G material is about 5 percent of that for the CL material. For a bending stress of 6000 psi, this percentage is about 10. The dynamic creep tension data show that, for a mean stress of 4000 psi, the creep deformation of the G material is about 10 percent of that for the CL laminate.

The foregoing comparison of creep behavior is based on periods of time covered by the tests. It is important, however, to determine a means of extrapolation of the data which will give an approximation of what the creep deformation will be for periods of time greater than those covered by tests and approaching the estimated life in service. In published investigations (reference 2) on plastics dealing with creep tension tests, a common method has been to plot the creep-time data on a log-log plot and to assume a linear relation between the creep deformations and time when plotted in this way. That is, it is assumed that for a particular stress value the creep is $e_t = kt^n$, where t is the time and k and n are experimental constants. With such a relation, the data can be extrapolated and the creep e_t can be determined for time values t not covered by the test. Unfortunately, this creep-time relation is not adequate for the data obtained in this report except for the static tension creep results. For this reason, and in order to determine a creep-stress relation, the log-log, log and hyperbolic sine methods (reference 1) of interpretation were applied to the test data. All three methods of interpretation assume a constant creep rate so that, where necessary, straight lines were assumed to represent approximately the creep-time data in figures 19 to 40 for periods of time beyond the initial creep. An inspection of these figures shows that the approximation of the data by straight lines for most of the lower stress values is good except for the tension creep data. For the higher stress values there is a divergence from a straight line. It should be noted, however, that these higher stresses are beyond working stress values. The slopes of the assumed straight lines in figures 19 to 40 are called the creep rates and their values are given in tables 13 to 18. The three methods of interpretation were applied to the five materials and four types of creep tests. Creep rate-stress relations obtained showed that no one of these methods could be considered to be sufficiently accurate to interpret the test data. For this reason, these results are not included in this report.

CONCLUSIONS

1. The relative values of the mechanical properties of the laminates in tension, compression, bending, and torsion are not in the same order for all types of tests.

2. The effect of repeated stressing to 100 cycles in tension and compression on the mechanical properties varied. For most tests, however, there was a decrease in ductility and stiffness, and an increase in yield strength.

3. The creep resistance of the laminates was found to vary with the ultimate tensile strength for all tests except the torsion creep tests on square specimens.

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The Pennsylvania State College,
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TABLE 1 - DESCRIPTION OF LAMINATES

Laminate		CL	C	R	P	G
Manufacturer		Synthane Corp.	Synthane Corp.	Formica Ins. Co.	Cons. Water Power & Paper Co.	---
Thickness (in.)		0.536	0.476	0.491	0.509	0.505
Density(gm/cm^3)		1.29	1.36	1.37	1.42	1.87
Resin	Type	Phenolic	Phenolic	Phenolic	Phenolic	Unsaturated Polyester
	Identification	Bakelite BV-16.887	Bakelite BV-1112	91-L	Bakelite No.16526	Plaskon 900
	Content by % Wt.	51	47	37-90	30 (nominal)	43
Reinforcement	Kind of Fabric	Army Duck	Army Duck	Rayon-cotton fabric	Paper	Glass fabric Heat treated
	Ply Arrangement	Crossed	Crossed	Crossed	Crossed	Parallel
	Fabric Weave	---	---	3/1 Twill	---	---
	Fabric Wt.-OZ/yd^2	10.38	10.38	12.5	---	---
Molding Conditions	Molding Pressure (p.s.i.)	180	1800	1100	250	40
	Molding Temp. (°F)	320	320	320	310 ± 10	180-220
	Time of Cycle (min) for heating	50	50	---	Fast as possible	2hrs.at 160° F 2hrs.at 180° F 2hrs.at 200° F 2hrs.at 220° F
	Time of Cycle (min) for Cooling	---	---	20	Cooled in still air at 75° F	---

TABLE 2 - MECHANICAL PROPERTIES IN STATIC TENSION

Mat.	Spec. No.	Area A sq.in.	Yield Strength S_{yt} psi	Ultimate Strength S_T psi	Stiffness $E_t \times 10^{-6}$	Ductility 100 e_T %
CL	1	0.204	5,700	9,100	0.68	5.5
	2	0.198	4,500	9,300	0.63	5.5
	Aver.		5,100	9,200	0.66	5.5
C	1	0.177	5,100	11,300	0.84	3.3
	2	0.177	5,700	11,300	1.07	3.7
	Aver.		5,400	11,300	0.96	3.5
R	1	0.180	7,700	25,000	1.48	3.4
	2	0.184	7,400	24,500	1.45	3.4
	Aver.		7,600	24,800	1.47	3.4
P	1	0.190	19,300	25,200	2.58	1.4
	2	0.190	24,300	25,200	2.11	1.5
	Aver.		21,800	25,200	2.35	1.5
G	1	0.188	37,300	37,300	2.49	1.5
	2	0.189	39,200	39,200	2.67	1.5
	Aver.		38,300	38,300	2.58	1.5

TABLE 3 - MECHANICAL PROPERTIES IN STATIC COMPRESSION

Mat.	Spec. No.	Area A sq.in.	Yield Strength S_{yc} psi	Ultimate Strength S_C psi	Stiffness $E_c \times 10^{-6}$ psi	Ductility 100 e_C %
CL	1	0.279	7,900	21,500	0.68	1.4
	2	0.277	6,900	21,600	0.59	1.2
	Aver.		7,400	21,600	0.64	1.3
C	1	0.236	8,500	21,200	0.77	1.07
	2	0.238	8,100	21,400	0.71	0.72
	Aver.		8,300	21,300	0.74	0.90
R	1	0.254	8,400	19,200	1.57	0.40
	2	0.252	8,200	19,600	1.84	0.44
	Aver.		8,300	19,400	1.71	0.42
P	1	0.254	10,600	19,800	2.39	0.47
	2	0.255	9,800	19,900	2.71	0.45
	Aver.		10,200	19,900	2.55	0.46
G	1	0.258	40,800	40,800	2.97	0.15
	2	0.264	41,000	41,000	2.81	0.14
	Aver.		40,900	40,900	2.89	0.14

TABLE 4 - MECHANICAL PROPERTIES IN STATIC BENDING

Mat.	Spec. No.	Width b in.	Depth d in.	Ultimate Strength S_B psi	Stiffness $E_b \times 10^{-6}$ psi	Ductility y_b in.
CL	1	0.547	1.122	16,700	0.79	0.43
	2	0.542	1.123	16,400	0.79	0.39
	3	0.545	1.121	16,800	0.87	0.43
	Aver.			16,600	0.82	0.42
C	1	0.473	1.155	17,900	0.93	0.31
	2	0.473	1.143	17,900	0.93	0.35
	3	0.473	1.154	18,700	0.93	0.36
	Aver.			18,200	0.93	0.34
R	1	0.481	1.129	31,400	1.58	0.41
	2	0.481	1.123	29,600	1.58	0.37
	3	0.478	1.121	31,900	1.59	0.39
	Aver.			31,000	1.58	0.39
P	1	0.505	1.127	31,100	--	0.16
	2	0.503	1.123	32,100	--	0.19
	3	0.502	1.130	31,100	--	0.16
	Aver.			31,400	2.48*	0.17
G	1	0.506	1.117	53,400	2.39	0.21
	2	0.517	1.163	49,600	2.55	0.20
	3	0.515	1.142	44,600	2.34	0.20
	Aver.			49,200	2.43	0.20

*Value given is average of 6 tests on specimens 1/2" x 1/2" x 6" span.

TABLE 5 - MECHANICAL PROPERTIES IN STATIC TORSION

Square Cross-Sections

Mat.	Spec. No.	Dimen. t in.	Ultimate Strength S_s psi	Stiffness $E_s \times 10^{-6}$ psi	Ductility θ_s degrees
CL	1	0.521	5,900	0.11	90
	2	0.528	5,200	0.13	85
	3	0.521	5,400	0.13	94
	Aver.		5,500	0.12	90
C	1	0.487	10,700	0.25	105
	2	0.485	9,600	0.26	99
	3	0.487	9,900	0.28	95
	Aver.		10,100	0.26	100
R	1	0.491	5,400	0.25	299
	2	0.490	5,500	0.23	288
	3	0.484	4,800	0.19	340
	Aver.		5,200	0.22	309
P	1	0.506	5,900	0.36	18
	2	0.506	5,700	0.36	17
	3	0.507	5,600	0.36	17
	Aver.		5,700	0.36	17
G	1	0.502	7,300	0.46	60
	2	0.501	7,100	0.51	60
	3	0.508	8,200	0.56	62
	Aver.		7,500	0.51	61

TABLE 6 - MECHANICAL PROPERTIES IN STATIC TORSION

Round Cross-Sections

Mat.	Spec. No.	Dia. D in.	Ultimate Strength S_s psi	Stiffness $E_s \times 10^{-6}$ psi	Ductility θ_s degrees
CL	1	0.502	4,800	--	180
	2	0.500	4,800	0.26	170
	3	0.501	4,800	0.26	
	Aver.		4,800	0.26	175
C	1	0.444	8,400	0.35	110
	2	0.439	7,500	0.31	115
	3	0.464	7,400	0.26	112
	Aver.		7,800	0.31	112
R	1	0.476	3,600	0.19	360
	2	0.473	4,000	0.20	420
	3	0.474	4,000	0.21	385
	Aver.		3,900	0.20	388
P	1	0.501	4,500	0.40	17
	2	0.480	4,600	0.38	18
	3	0.485	5,000	0.36	21
	Aver.		4,700	0.38	19
G	1	0.500	4,600	0.49	70
	2	0.490	7,400	0.59	30
	3	0.486	6,100	0.59	26
	Aver.		6,000	0.56	42

TABLE 7 - COMPARISON OF MECHANICAL PROPERTIES

FOR FIVE LAMINATES

Rating		1		2		3		4		5	
Type of Test	Mechanical Property	Mat.	%	Mat.	%	Mat.	%	Mat.	%	Mat.	%
Tension	Ultimate Str.	G	100	P	66	R	65	C	30	CL	24
	Yield Str.	G	100	P	57	R	20	C	14	CL	13
	Stiffness	G	100	P	91	R	57	C	37	CL	25
	Ductility	CL	100	C	63	R	62	G	27	P	26
Compression	Ultimate Str.	G	100	CL	53	C	52	P	49	R	48
	Yield Str.	G	100	P	25	C	20	R	20	CL	18
	Stiffness	G	100	P	88	R	59	C	26	CL	22
	Ductility	CL	100	C	69	P	35	R	32	G	11
Bending	Ultimate Str.	G	100	P	64	R	63	C	37	CL	34
	Stiffness	P	100	G	98	R	64	C	37	CL	33
	Ductility	CL	100	R	93	C	81	G	49	P	41
Torsion (round)	Ultimate Str.	C	100	G	77	CL	62	P	60	R	50
	Stiffness	G	100	P	66	C	55	CL	48	R	35
	Ductility	R	100	CL	34	C	29	G	11	P	5
Torsion (Square)	Ultimate Str.	C	100	G	75	P	57	CL	55	R	52
	Stiffness	G	100	P	71	C	51	R	44	CL	24
	Ductility	R	100	C	32	CL	29	G	20	P	5

TABLE 8 - MECHANICAL PROPERTIES IN TENSION AFTER

100 STRESS REPETITIONS IN TENSION

TO 2/3 ULTIMATE STRENGTH

Mat.	Spec. No.	Dimensions b in.	Dimensions d in.	Yield Strength S_{yt} psi	Ultimate Strength S_t psi	Stiffness $E_t \times 10^{-6}$ psi	Ductility %
CL	1	0.376	0.538	6,200	9,000	0.47	4.4
	2	0.377	0.542	6,300	8,900	0.44	4.4
	Aver.			6,300	9,000	0.46	4.4
C	1	0.377	0.470	7,900	10,500	0.65	2.5
	2	0.363	0.467	7,800	11,200	0.77	2.6
	Aver.			7,900	10,900	0.71	2.6
R	1	0.372	0.483	22,500	24,600	0.96	2.6
	2	0.372	0.478	21,900	25,000	1.05	2.8
	Aver.			22,200	24,800	1.01	2.7
P	1	0.374	0.510	23,100	27,300	2.27	1.5
	2	0.381	0.513	22,500	27,200	2.33	1.6
	Aver.			22,800	27,300	2.30	1.6
G	1	0.366	0.502	35,900	35,900	2.70	1.2
	2	0.366	0.506	35,700	35,700	2.67	1.4
	Aver.			35,800	35,800	2.69	1.3

TABLE 9 - MECHANICAL PROPERTIES IN COMPRESSION AFTER

100 STRESS REPETITIONS IN COMPRESSION

TO 2/3 ULTIMATE STRENGTH

Mat.	Spec. No.	Dimensions b in.	Dimensions d in.	Yield Strength S_{yc} psi	Ultimate Strength S_c psi	Stiffness $E_c \times 10^{-6}$ psi	Ductility %
CL	1	0.499	0.549	7,000	20,800	0.55	0.73
	2	0.498	0.550	5,200	20,800	0.57	0.83
	Aver.			6,100	20,800	0.56	0.78
C	1	0.482	0.497	9,400	21,200	0.87	0.44
	2	0.478	0.498	11,800	22,300	0.75	0.73
	Aver.			10,600	21,800	0.81	0.58
R	1	0.480	0.503	14,500	19,100	0.98	0.31
	2	0.482	0.502	12,100	19,200	1.36	0.34
	Aver.			13,300	19,200	1.17	0.33
P	1	0.499	0.500	15,000	19,700	1.43	0.47
	2	0.501	0.504	15,400	19,050	1.31	0.38
	Aver.			15,200	19,400	1.37	0.42
G	1	0.501	0.519	36,500	36,500	3.35	0.11
	2	0.500	0.500	38,000	38,000	3.63	0.11
	Aver.			37,300	37,300	3.49	0.11

TABLE 10 - MECHANICAL PROPERTIES IN COMPRESSION AFTER 100 STRESS REPETITIONS IN TENSION TO 2/3 ULTIMATE STRENGTH

Mat.	Spec. No.	Dimensions b in.	Dimensions d in.	Yield Strength S_{yc} psi	Ultimate Strength S_c psi	Stiffness $E_c \times 10^{-6}$ psi	Ductility %
CL	1	0.376	0.538	12,600	18,300	0.41	0.61
	2	0.378	0.550	12,000	17,300	0.39	0.56
	Aver.			12,300	17,800	0.40	0.58
C	1	0.374	0.475	11,300	19,700	0.51	0.62
	2	0.387	0.469	8,300	19,300	0.62	0.64
	Aver.			9,800	19,500	0.57	0.63
R	1	0.384	0.504	13,100	17,600	1.13	0.36
	2	0.373	0.505	10,400	17,600	1.09	0.34
	Aver.			11,800	17,600	1.11	0.35
P	1	0.375	0.509	8,700	19,400	2.68	0.47
	2	0.374	0.510	8,900	19,400	2.38	0.49
	Aver.			8,800	19,400	2.53	0.48
G	1	0.349	0.507	36,800	36,800	2.97	0.13
	2	0.366	0.509	35,000	35,000	3.14	0.13
	Aver.			35,900	35,900	3.05	0.13

TABLE 11 - INFLUENCE OF REPEATED STRESSING ON THE MECHANICAL PROPERTIES

Type of Test	Material	% Change in Mechanical Property: Ultimate Strength	Yield Strength	Stiffness	Ductility
Tension-Tension	CL	-3	+22	-31	-20
	C	-4	+45	-26	-29
	R	0	+193	-31	-21
	P	+8	+4	-2	+8
	G	-6	-6	+4	-11
Comp.-Comp.	CL	-3	-18	-12	-40
	C	+2	+27	+10	-35
	R	-1	+60	-32	-21
	P	-3	+49	-46	-8
	G	-9	-9	+21	-26
Tension-Comp.	CL	-17	+67	-37	-55
	C	-8	+17	-23	-30
	R	-6	+51	-62	+2
	P	+9	-1	+24	+2
	G	-12	-12	+5	-13

TABLE 12 - ENERGY DISSIPATED PER CYCLE FOR STRESSING IN TENSION TO TWO-THIRD THE ULTIMATE STRESS

Mat.	Ultimate Tensile Strength psi	Spec. No.	Energy Dissipated per Cycle (in.lb. per cu.in.)
CL	9200	9CL	25.7
		10CL	25.1
		Aver.	25.4
C	11,300	23C	18.2
		24C	20.7
		Aver.	20.0
R	24,700	11R	53.5
		12R	54.5
		Aver.	54.0
P	25,200	27P	41.3
		28P	41.6
		Aver.	41.5
G	38,300	7G	9.38
		8G	9.45
		Aver.	9.42

TABLE 13 - STATIC TENSION CREEP TEST DATA

Mat.	Spec. No.	Area sq.in.	Load lb.	Stress S_t psi	Creep Rate C_t in./in./hr. X 10^6	Creep e_t at 1400 hr. in. x 500
CL	1	0.207	550	2,650	0.50	4.0
	2	0.200	804	4,000	1.10	8.5
	3	0.202	917	4,540	1.50	10.0
	4	0.200	1,037	5,230	1.20	11.0
	5	0.208	1,230	5,920	3.10	26.0
	6	0.207	1,359	6,570	3.20	26.7
C	1	0.174	550	3,160	0.90	3.8
	2	0.174	804	4,610	1.80	7.7
	3	0.176	917	5,200	1.90	10.7
	4	0.176	1,077	6,130	2.00	14.8
	5	0.181	1,230	6,830	3.20	18.2
	6	0.175	1,387	7,950	6.00	--
R	1	0.181	838	4,640	1.00	4.8
	2	0.178	1,156	6,520	1.60	7.1
	3	0.178	1,367	7,700	1.90	8.5
	4	0.178	1,695	9,540	2.30	10.4
	5	0.178	1,805	10,130	2.30	12.8
	6	0.178	2,151	12,110	3.00	14.9
	7	0.177	2,532	14,260	5.20	23.6
	8	0.178	2,550	14,310	6.10	28.1
P	1	0.190	1,110	5,850	0.53	2.8
	2	0.181	1,775	9,780	0.98	3.7
	3	0.182	2,099	11,520	1.15	6.3
	4	0.193	2,829	14,670	1.08	9.0
	5	0.187	2,830	15,120	1.36	10.5
G	1	0.168	838	4,980	0.05	1.12
	2	0.171	1,491	8,800	0.20	2.22
	3	0.174	2,265	13,100	0.26	3.67
	4	0.174	2,993	17,300	0.60	5.50
	5	0.182	3,879	21,300	0.40	6.05
	6	0.171	4,491	26,300	0.25	6.85

TABLE 14 - STATIC BENDING CREEP TEST DATA

Mat.	Spec. No.	Dimensions b in.	Dimensions d in.	Moment M in.lb.	Stress S_b psi	Creep Rate C_b in./hr. x 5X10^5	Creep Def. at 1000 hr. in. x 1000 (2"gage length)
CL	1	0.540	1.125	468	4,120	0.57	7.50
	2	0.540	1.125	591	5,190	0.68	10.70
	3	0.543	1.126	697	6.080	0.80	14.30
	4	0.537	1.126	788	6,950	1.18	--
	5	0.542	1.124	838	7,340	1.32	25.80
C	1	0.480	1.124	533	5,250	0.41	9.20
	2	0.475	1.122	624	6,260	0.23	9.70
	3	0.478	1.125	679	6,730	0.57	12.30
	4	0.478	1.125	767	7,600	0.84	14.56
	5	0.474	1.121	917	9,235	0.93	20.96
	6	0.474	1.124	932	9,350	0.91	--
R	1	0.479	1.127	532	5,260	0.28	4.50
	2	0.481	1.127	619	6,090	0.20	7.50
	3	0.479	1.121	771	6,430	0.31	9.80
	4	0.478	1.126	921	9,080	0.57	12.70
	5	0.476	1.119	1080	10,900	1.02	17.10
	6	0.480	1.120	1228	12,250	0.91	19.10
	7	0.480	1.095	1368	14,250	1.30	26.00
	8	0.482	1.100	1519	15,650	1.93	32.00
P	1	0.503	1.095	478	4,750	0.23	2.76
	2	0.504	1.096	771	7,650	0.23	4.80
	3	0.502	1.087	1062	10,750	0.50	6.84
	4	0.504	1.011	971	11,300	0.36	17.00
	5	0.504	1.001	1433	17,050	1.16	--
G	1	0.516	1.142	471	4,200	0.034	1.54
	2	0.498	1.164	788	7,000	0.023	2.60
	3	0.498	1.137	1078	10,050	0.011	2.04
	4	0.517	1.161	1379	11,850	0.125	4.52
	5	0.504	1.164	1686	14,800	0.091	3.50
	6	0.506	1.156	2279	20,200	0.318	8.60

TABLE 15 - STATIC TORSION CREEP TEST DATA - ROUND CROSS-SECTIONS

Mat.	Spec. No.	Dia. in.	Twisting Moment in. lb.	Shear Stress S_S psi	Creep Rate C_S deg/in/hr x 10^3	Creep Angle at 1000 hr. deg/in.
R	1	0.456	39.6	1,950	1.17	2.5
	2	0.475	51.5	2,580	1.82	7.0
	3	0.475	66.0	3,310	3.67	18.5
	4	0.463	75.8	3.890	Failed	--
P	1	0.495	33.4	1,400	0.33	1.75
	2	0.500	50.7	2,070	0.67	2.55
	3	0.502	58.2	2,340	0.67	2.80
	4	0.493	70.5	3,000	1.73	--
	5	0.499	79.4	3,260	1.94	--
	6	0.500	95.3	3,870	2.00	--
	7	0.500	111.2	4,550	Failed	--
G	1	0.501	54.5	2,210	0.67	1.83
	2	0.504	79.2	3,150	0.83	3.00
	3	0.497	92.0	3,810	Failed	--
	4	0.496	105.0	4,370	2.67	6.16

TABLE 16 - STATIC TORSION CREEP TEST DATA - SQUARE CROSS-SECTION

Mat.	Spec. No.	Dim. t(aver)	Twisting Moment in. lb.	Shear Stress S_S psi	Creep Rate C_S deg/in/hr. x 10^3	Creep Angle at 1000 hr. deg/in.
C	1	0.485	66.0	2,770	0.33	3.00
	2	0.488	99.1	4,100	0.50	4.67
	3	0.486	132.2	5,500	1.08	8.75
	4	0.486	165.0	6,900	1.83	15.25
R	1	0.488	39.6	1,635	0.42	1.83
	2	0.494	58.0	2,310	0.67	3.00
	3	0.492	81.5	3,300	1.50	5.84
	4	0.490	89.0	3,630	2.83	7.66
P	1	0.501	33.1	2,000	0.12	0.83
	2	0.505	70.5	4,250	0.30	1.80
	3	0.501	95.5	5,770	0.53	2.90
	4	0.505	112.0	6,760	0.75	3.84
G	1	0.510	66.0	2,390	0.47	1.60
	2	0.510	98.0	3,770	0.77	2.77
	3	0.500	120.5	4,630	1.17	4.07
	4	0.496	132.0	5,220	3.27	7.93

TABLE 17 - DYNAMIC TENSION CREEP TEST DATA

Material	Spec. No.	Weight W_s lb.	Area, A x 10^2 sq. in.	Stress S_m psi	Force F_s lb.	Stress S_t psi	Stress Ratio R_t	Creep Rate C_t in./in./hr. x 10^6	Creep, at 200 hr. in./in. x 10^3
CL	1	99.9	5.13	1,950	65.3	3,220	0.61	4.5	1.8
	2	119.5	5.10	2,340	70.7	3,740	0.63	3.0	4.0
	3	165.0	5.25	3,140	82.4	4,720	0.67	8.0	4.8
	4	187.0	5.00	3,740	93.3	5,620	0.67	9.0	8.4
C	1	80.0	2.76	2,890	66.2	5,310	0.55	5.5	3.9
	2	85.0	2.61	3,260	68.8	5,890	0.55	7.5	5.3
	3	91.8	2.58	3,530	70.8	6,070	0.58	10.0	8.2
	4	107.5	2.46	4,320	78.4	7,550	0.57	12.5	9.2
	5	121.2	2.54	4,770	82.5	8,020	0.60	17.5	10.6
P	1	121.2	2.70	4,480	61.0	6,760	0.66	1.3	2.1
	2	131.2	2.50	5,240	63.2	7,790	0.67	2.4	2.8
	3	183.6	2.56	7,170	73.8	10,050	0.71	3.5	3.3
	4	193.6	2.40	8,050	73.4	11,120	0.72	3.5	3.5
R	1	193.6	2.28	8,500	105.0	13,100	0.65	5.0	8.8
	2	221.2	2.37	9,250	113.0	14,100	0.66	5.5	14.7
	3	239.8	2.54	9,500	122.0	14,200	0.66	8.0	16.1
	4	260.9	2.52	10,350	141.0	15,950	0.65	6.5	18.6
G	1	256.0	2.57	9,980	51.1	11,920	0.84	0	3.1
	2	330.0	2.47	13,400	52.1	15,470	0.87	0	3.8
	3	380.2	2.66	14,300	Failed	--	--	--	--
	4	425.3	2.58	17,500	Failed	--	--	--	--

TABLE 18 - COMPARISON OF CREEP DEFORMATIONS

Type of Creep test		Stress psi	Creep Deformation of Material				
			CL	C	R	P	G
Static Tension Strain at 1400 hours in. per in. x 10^3		2,000	2.5	1.6	0.7	0.8	0.4
		4,000	8.2	5.8	2.3	1.6	1.0
		6,000	20.3	13.6	4.7	2.4	1.5
		8,000	--	--	7.9	3.3	2.0
		10,000	--	--	11.8	4.2	2.6
		12,000	--	--	17.1	5.7	3.1
		14,000	--	--	25.5	8.5	3.7*
		16,000	--	--	--	11.7*	4.3*
Static Bending Deflection at 1000 hrs. in. x 10^3 (2" gage length)		2,000	3.20	2.7	2.5	1.0	0.6
		4,000	7.2	6.0	5.0	2.4	1.0
		6,000	13.5	10.1	7.6	3.6	1.5
		8,000	--	15.6	10.3	5.2	2.0
		10,000	--	24.4*	14.2	6.7	2.6
		12,000	--	--	19.2	--	3.4
		14,000	--	--	25.4	--	4.8
		16,000	--	--	--	--	6.7*
Static Torsion Angle of Twist at 1000 hours Deg. per in.	Round Cross-section	2,000	--	--	2.7	2.4	1.6
		3,000	--	--	13.4*	4.1*	2.8
		4,000	--	--	--	7.1*	5.1
		5,000	--	--	--	11.4*	8.5*
	Square Cross-section	2,000	--	1.9	2.3	0.8	1.4
		3,000	--	3.2	4.5	1.2	2.0
		4,000	--	4.5	--	1.7	2.9
		5,000	--	6.9	--	2.2	5.0
		6,000	--	10.6	--	3.0	--
Dynamic Tension Strain at 200 hrs. in. per in. x 10^3		2,000	2.4	2.4	1.6	0.9	0.6
		4,000	9.0*	7.6	3.8	1.8	1.1
		6,000	--	--	6.6	2.7	1.7
		8,000	--	--	10.2	3.6	2.3
		10,000	--	--	16.5*	4.5*	2.8
		12,000	--	--	--	5.5*	3.4
		14,000	--	--	--	6.4*	4.0*

* Extrapolated Values

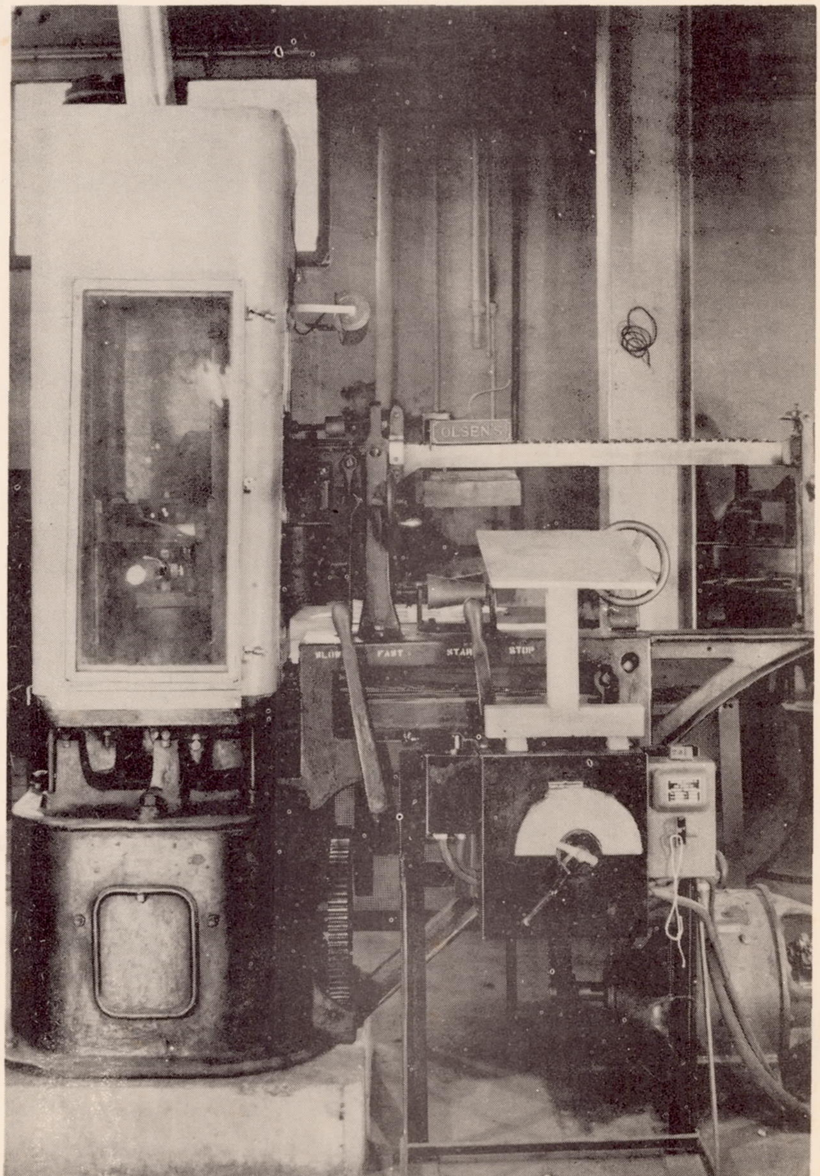


Figure 1.- Universal testing machine showing
enclosure for humidity control.

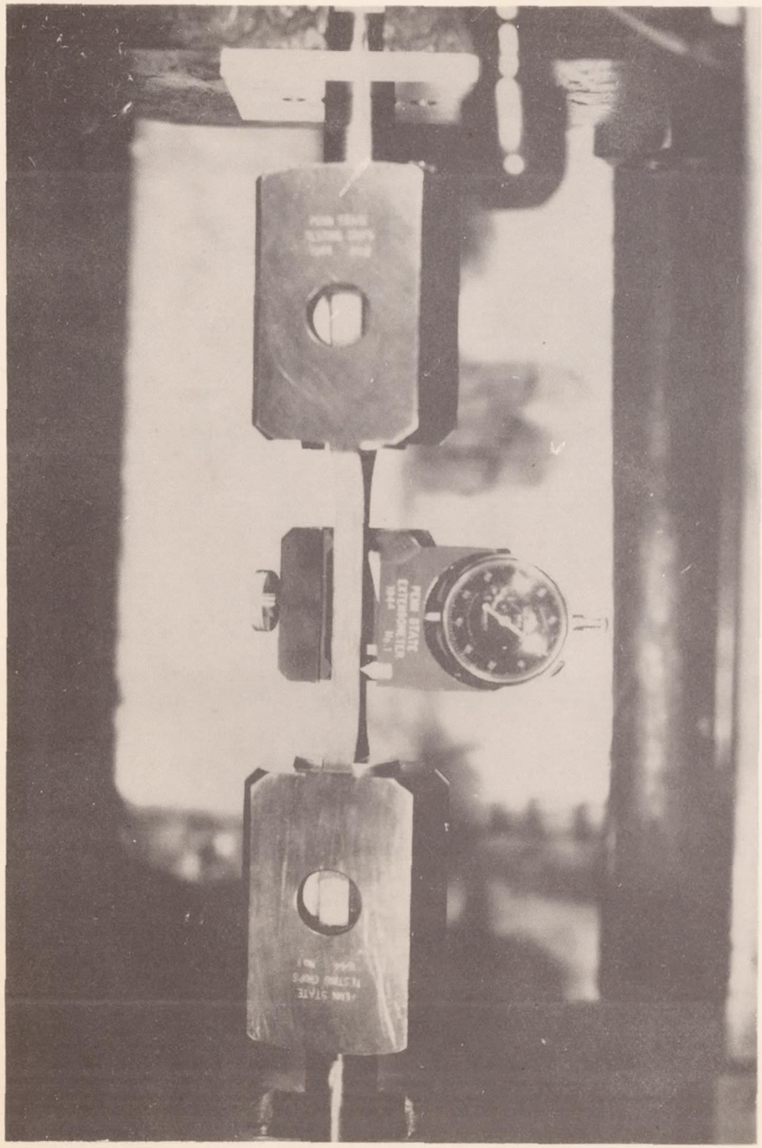


Figure 2.- Specimen assembly for tension tests.

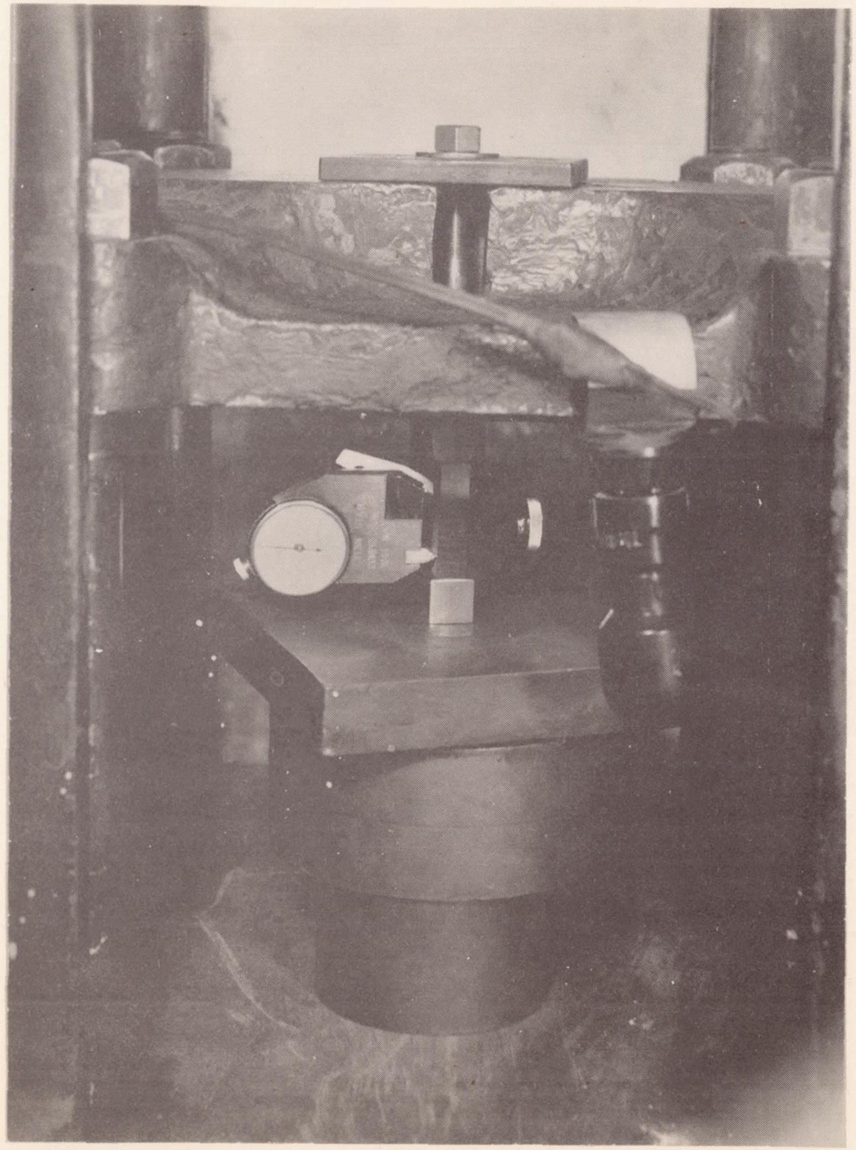


Figure 3.- Specimen assembly for compression tests.

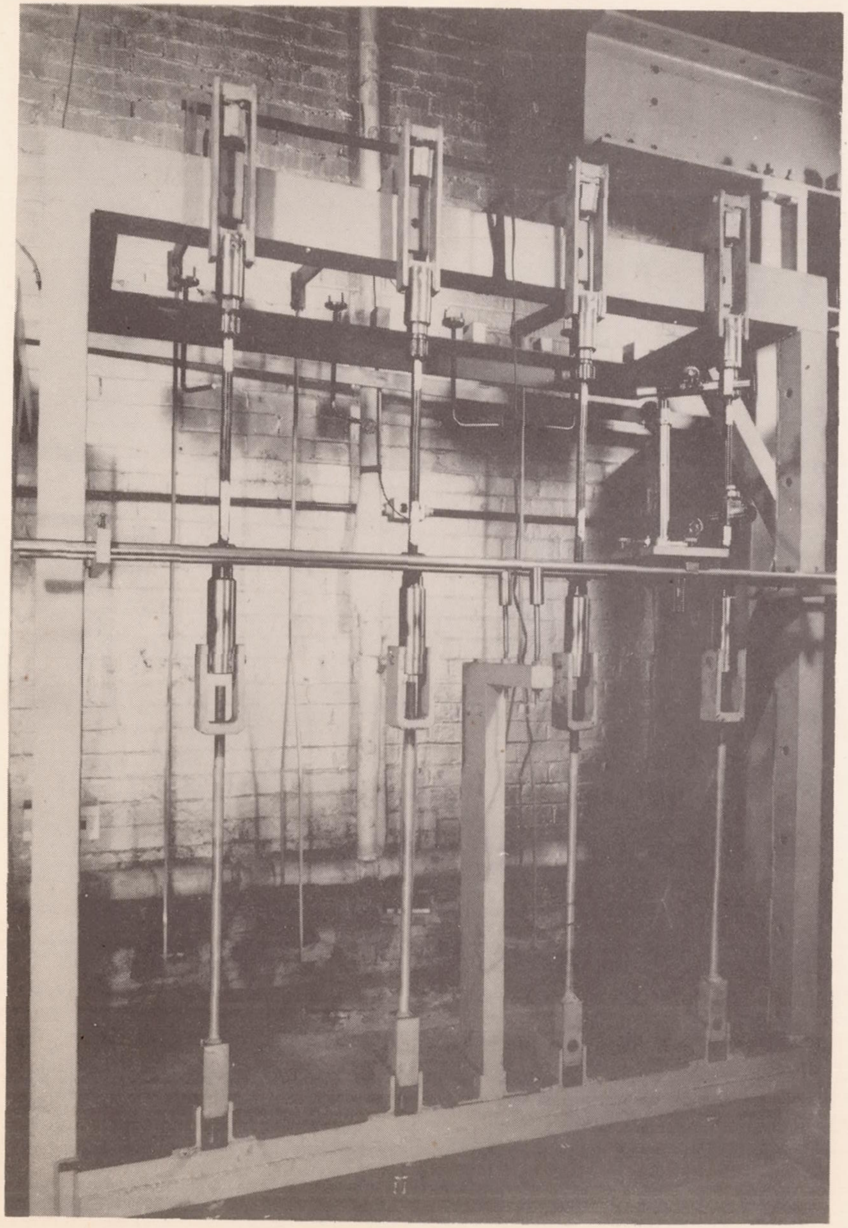


Figure 4.- Four unit static tension creep machine.

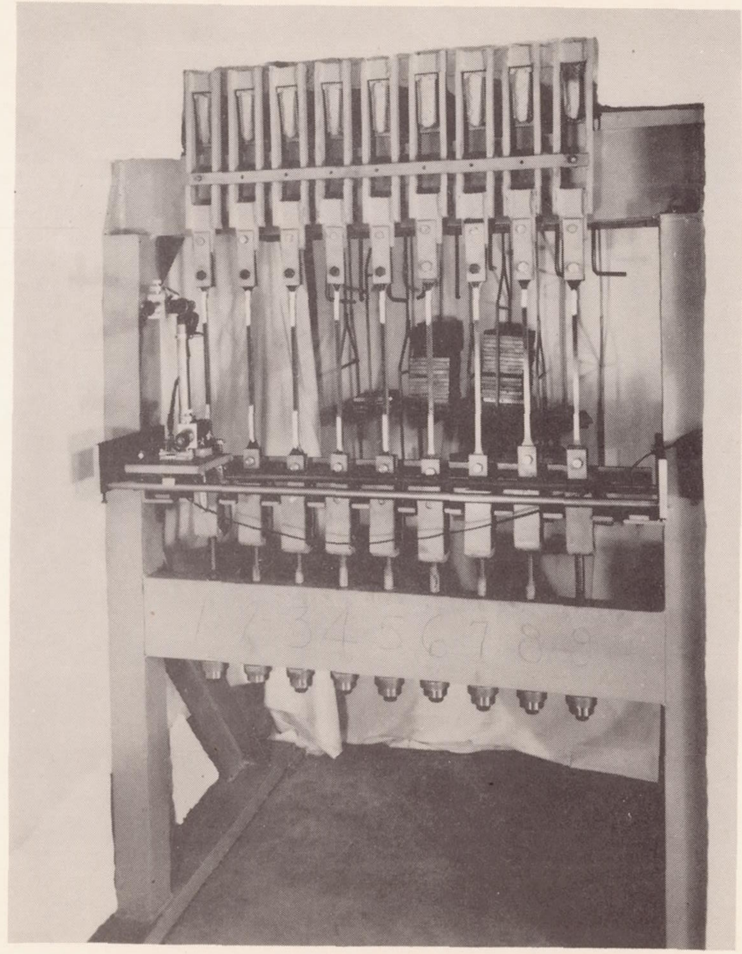


Figure 5.- Nine unit static tension creep machine.

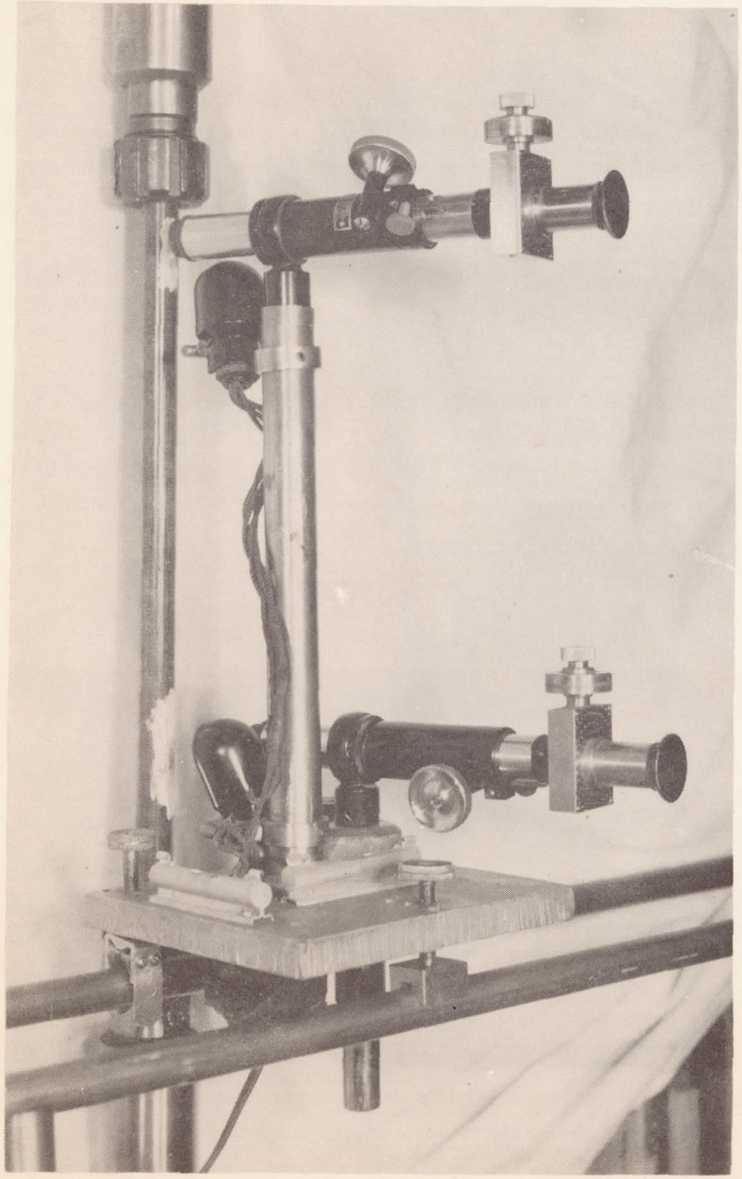


Figure 6.- Strain gage for measuring tension creep strains.

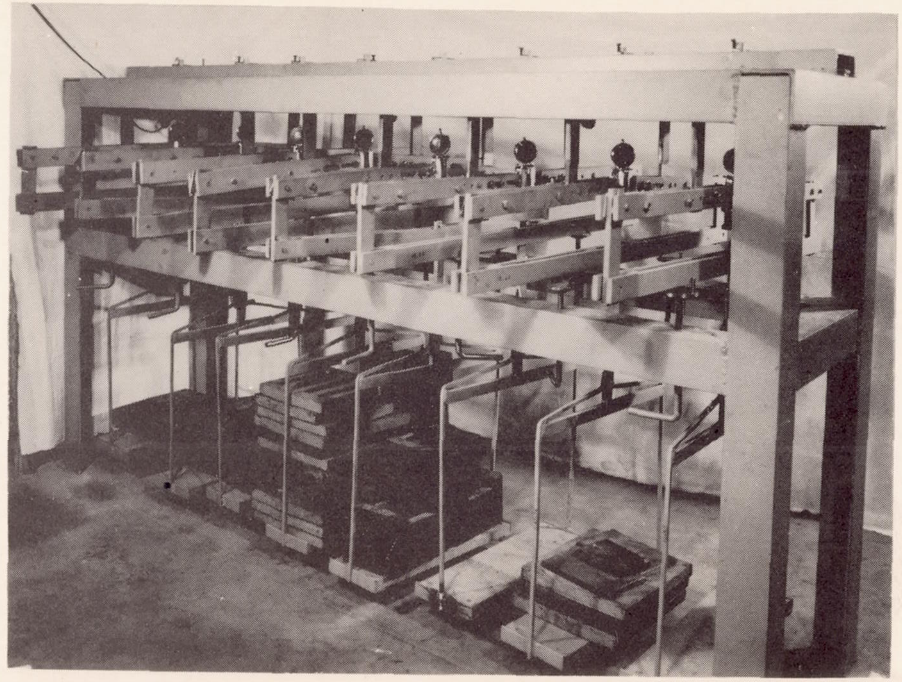


Figure 7.- Static creep bending machine.

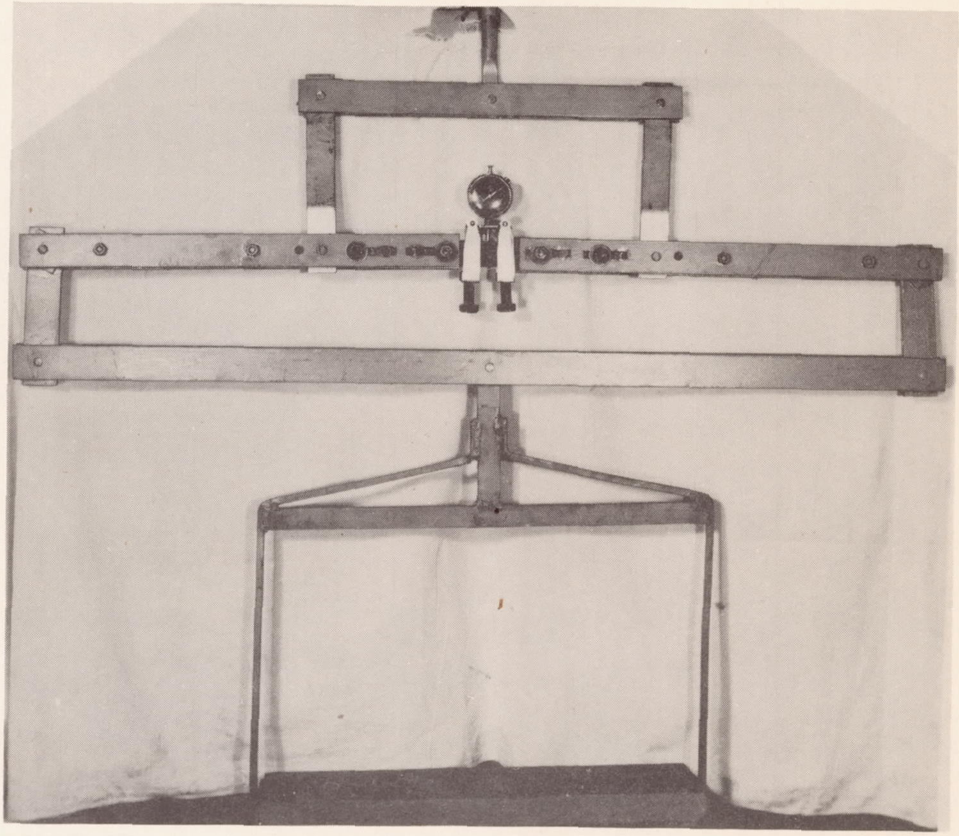


Figure 8.- Static creep bending unit showing method of loading.

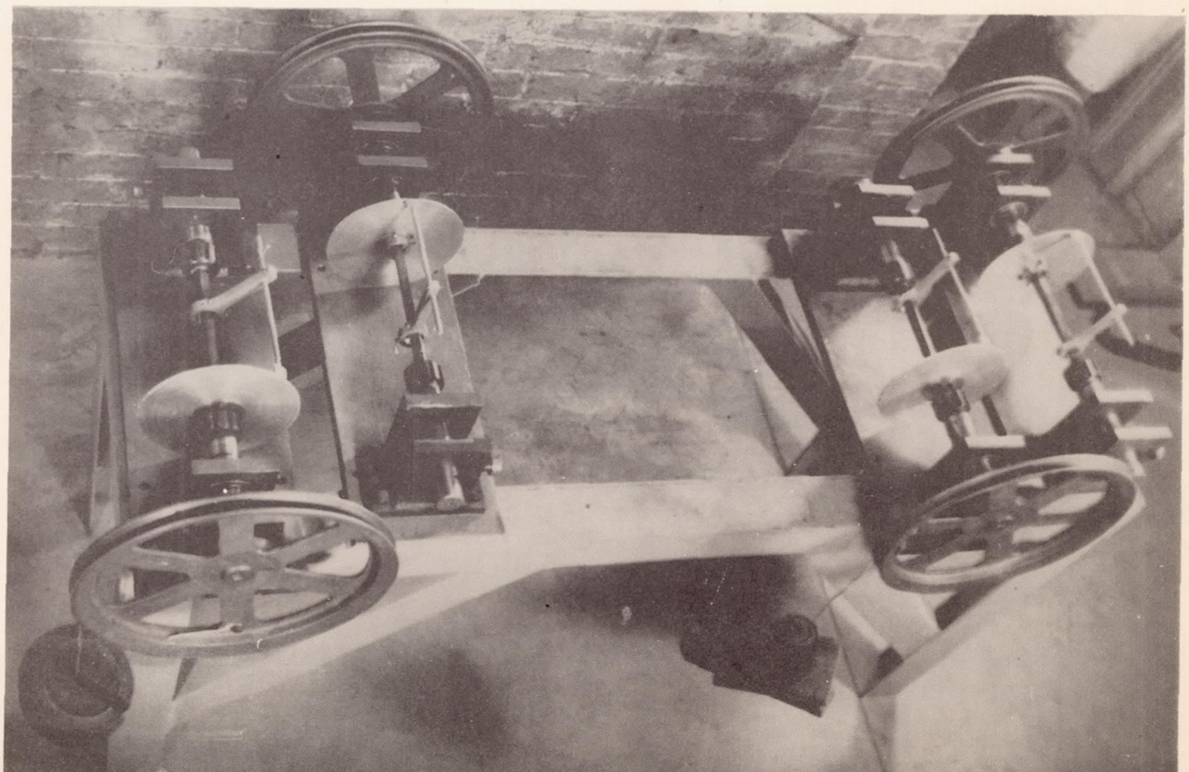


Figure 9.- Static creep torsion machine.

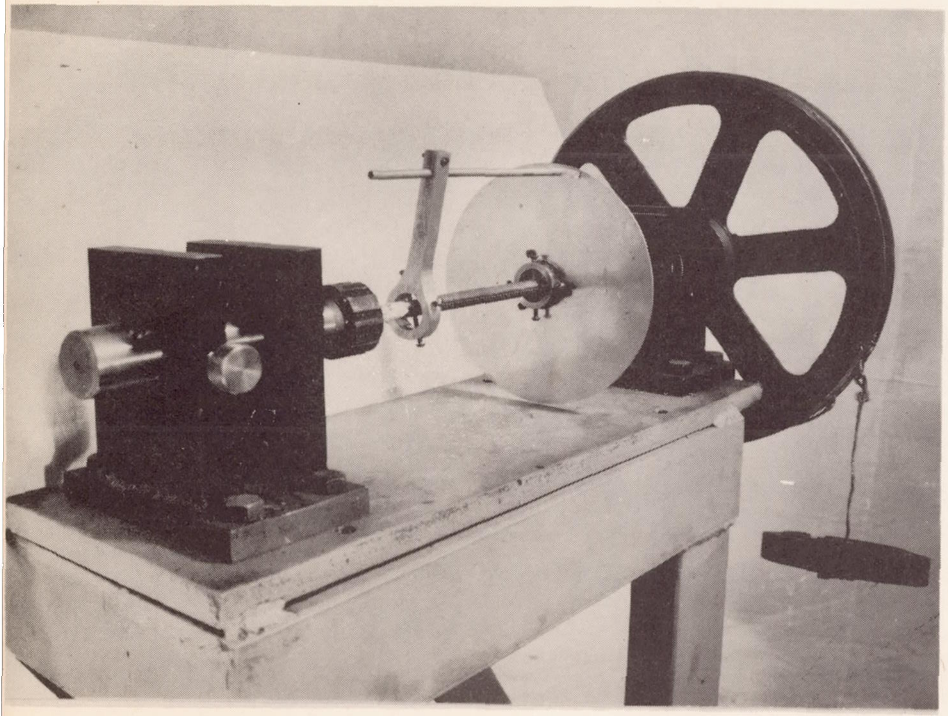


Figure 10.- Static creep torsion unit showing method of loading.

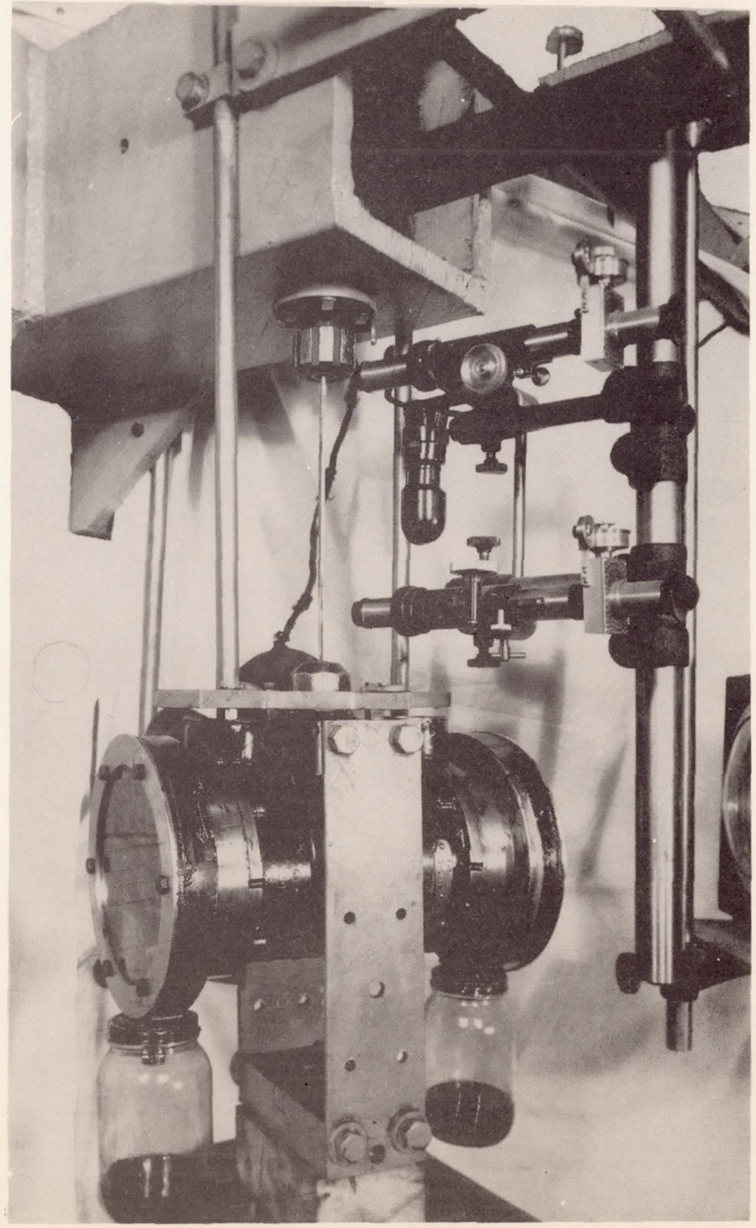
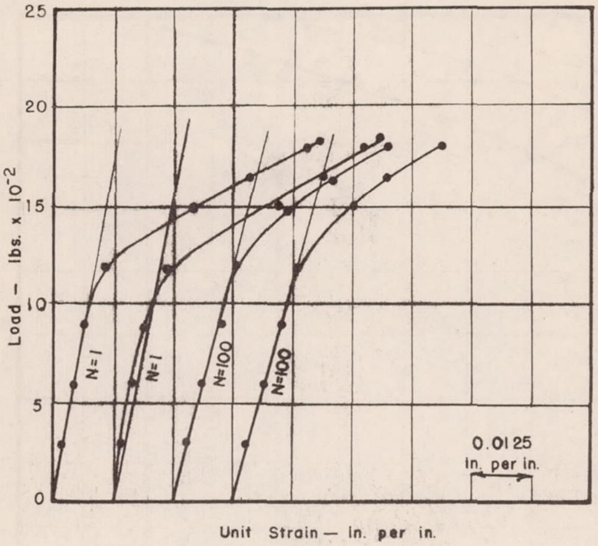
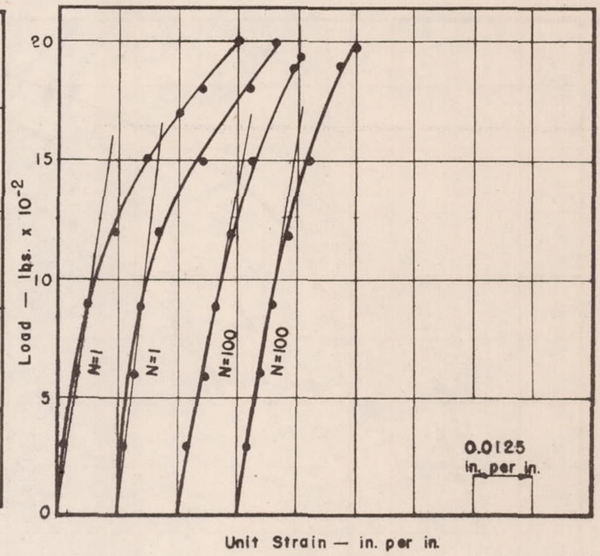


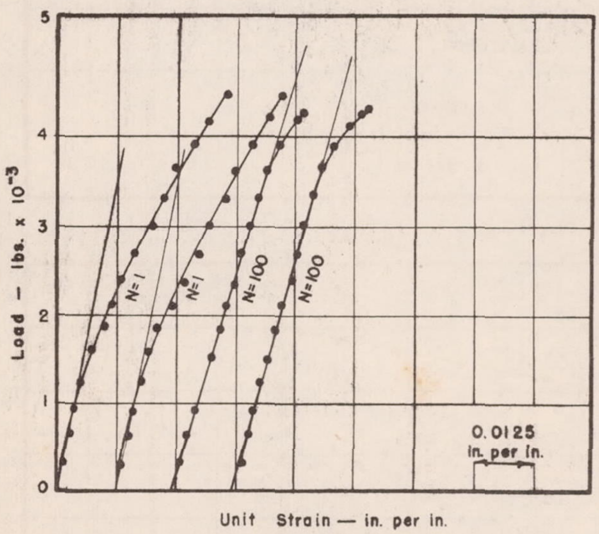
Figure 11.- Dynamic creep tension machine



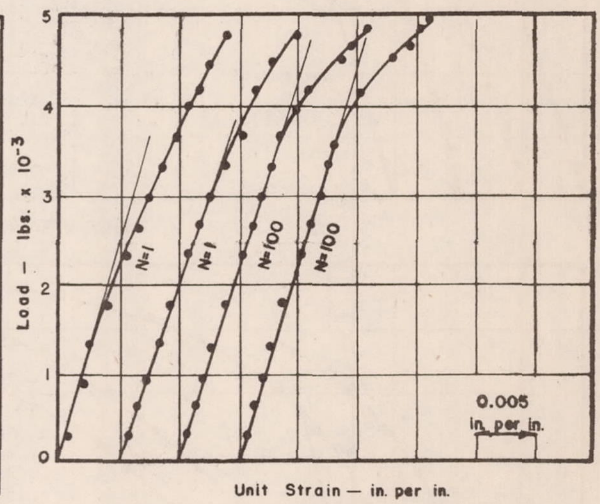
MATERIAL CL



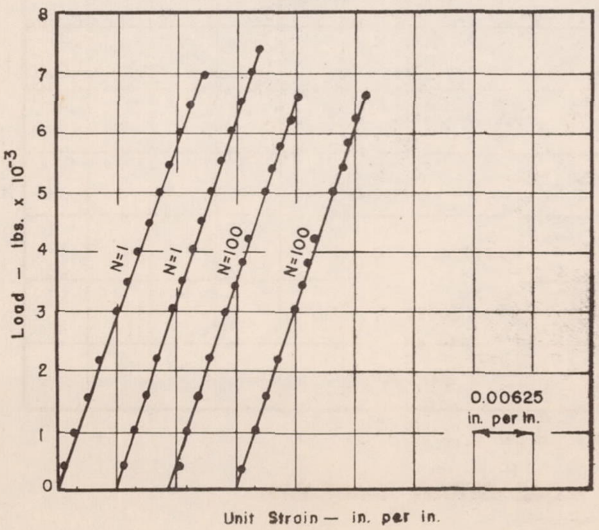
MATERIAL C



MATERIAL R



MATERIAL P

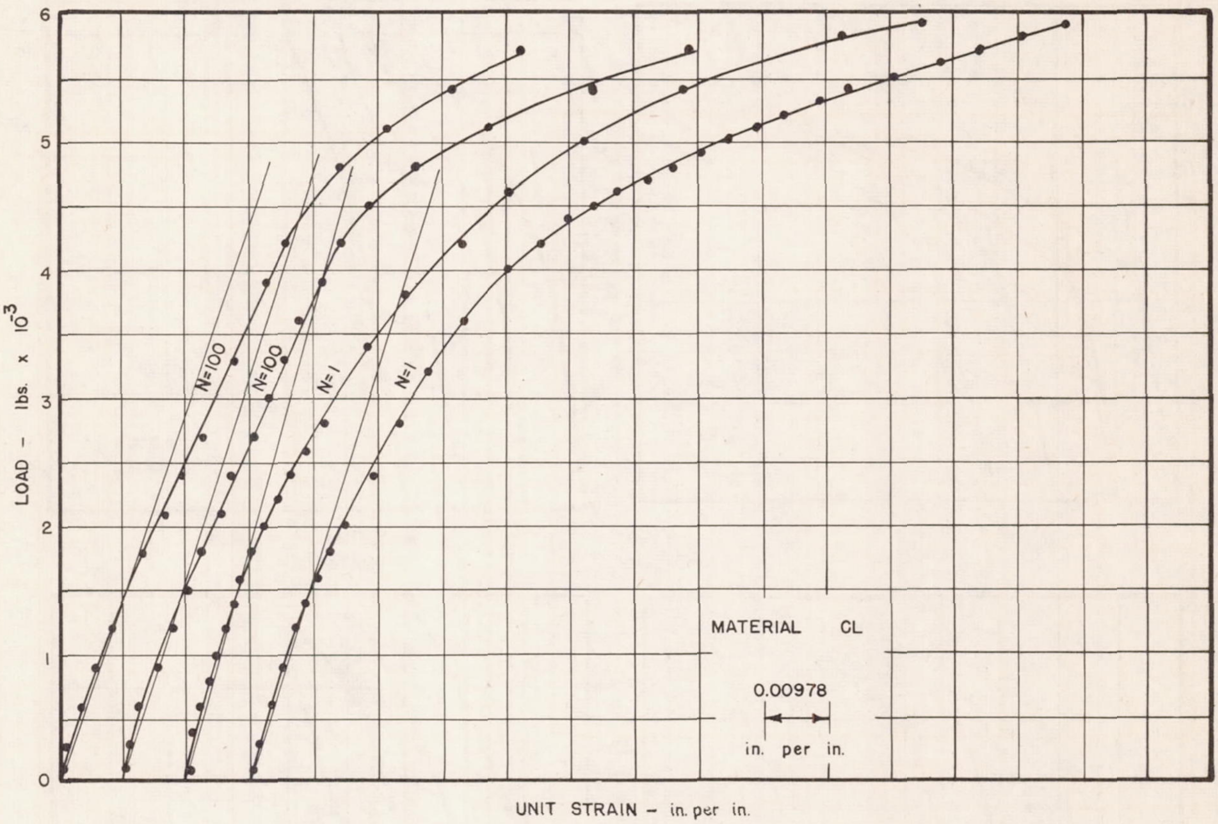


MATERIAL G

FIG. 12 –

STATIC TENSION

LOAD-STRAIN DIAGRAMS



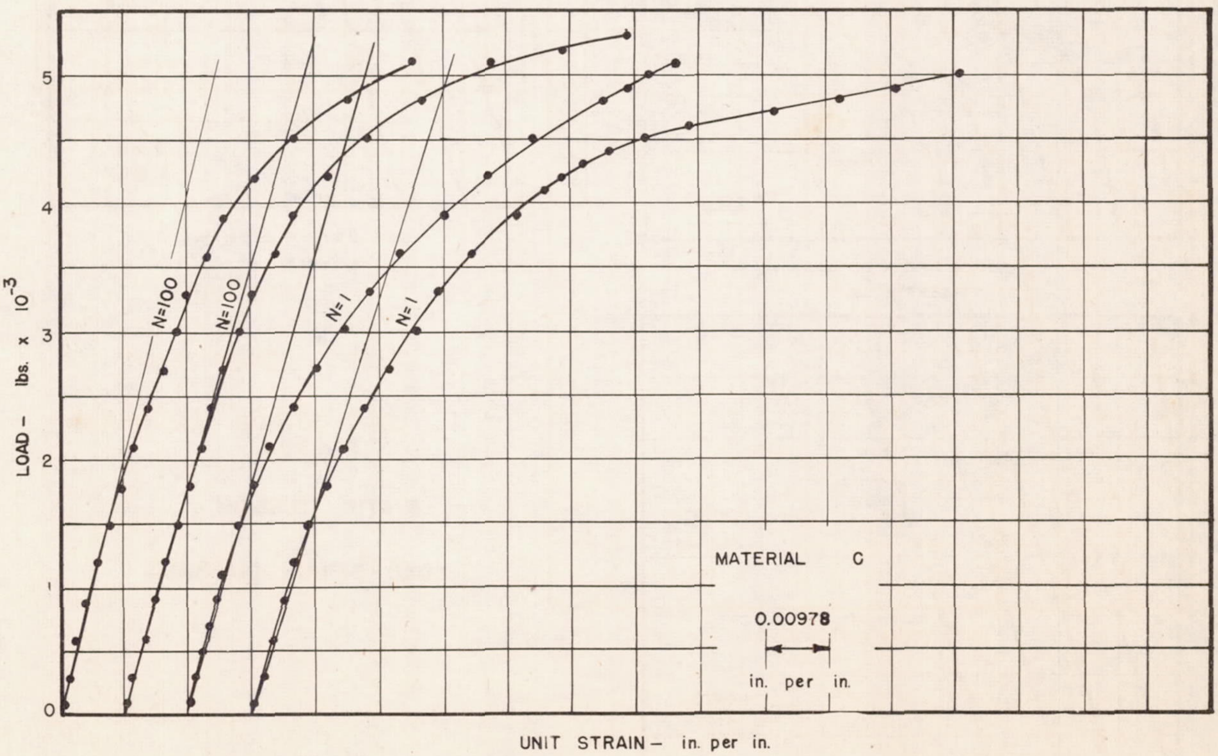
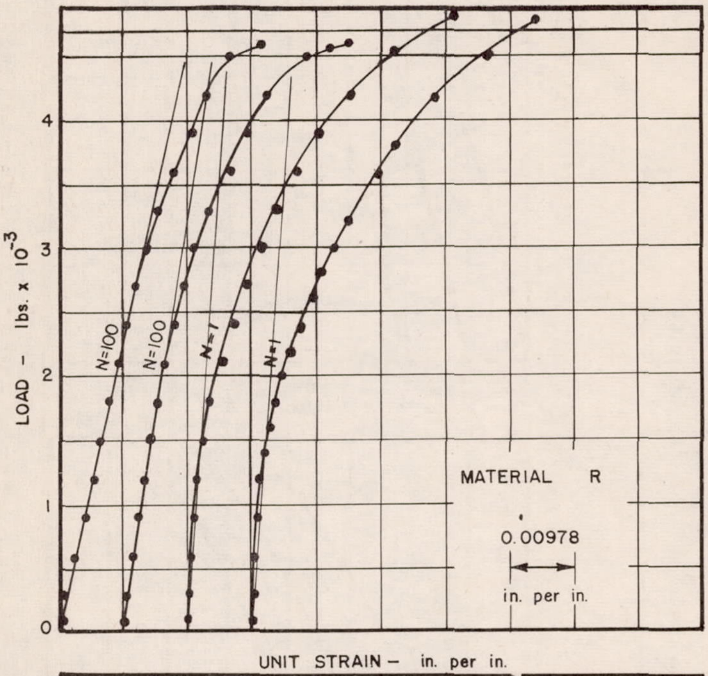
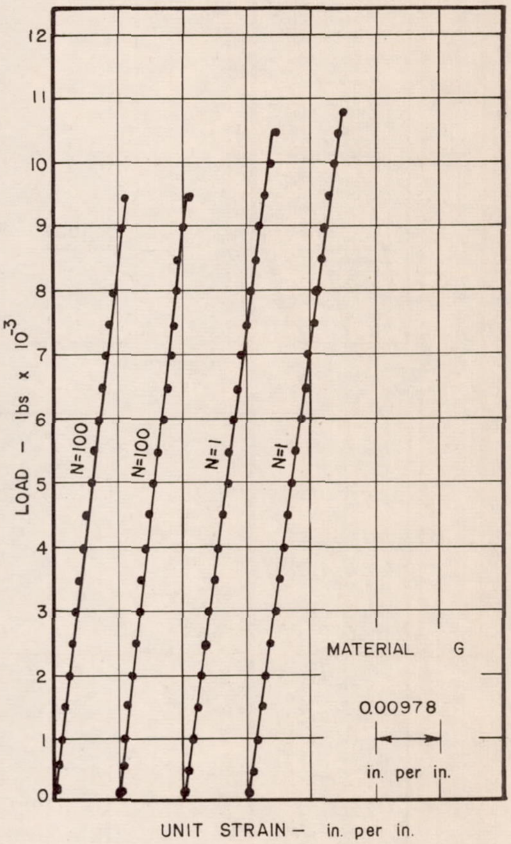


FIG. 13a - STATIC COMPRESSION LOAD-STRAIN DIAGRAMS





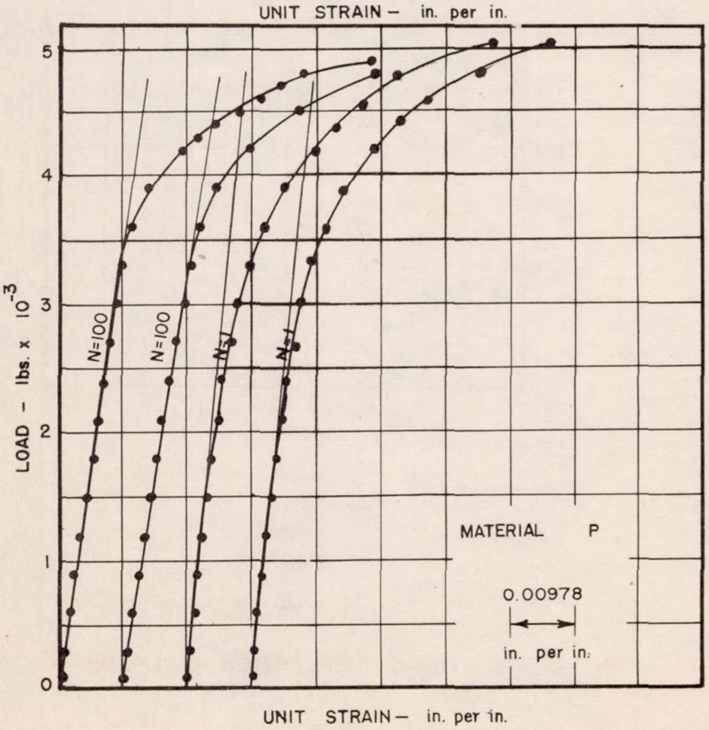
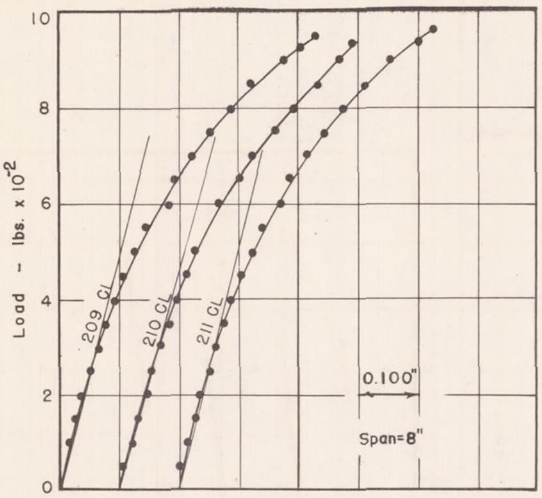


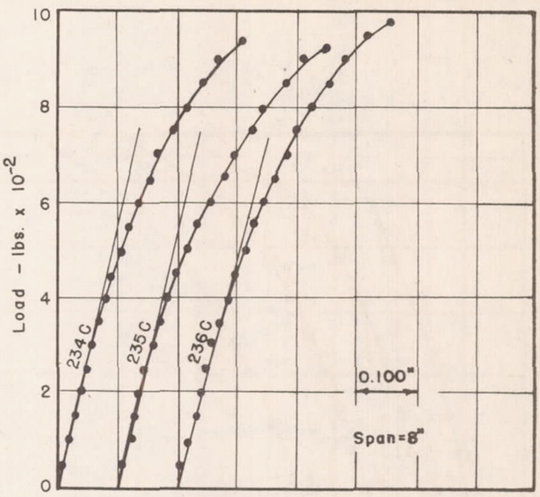
FIG. 13b -

STATIC COMPRESSION

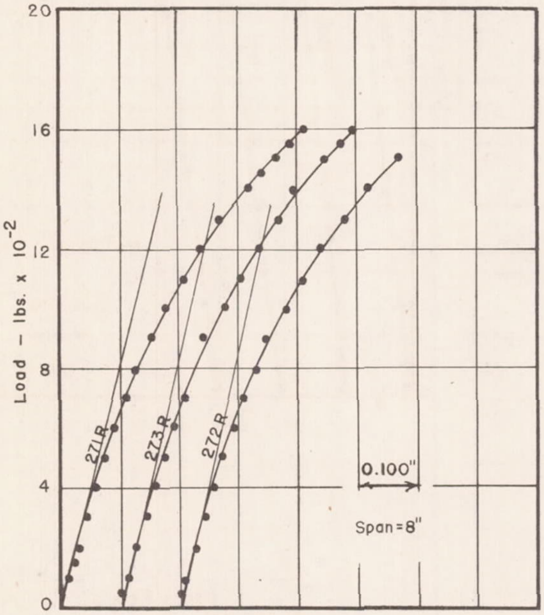
LOAD-STRAIN DIAGRAMS



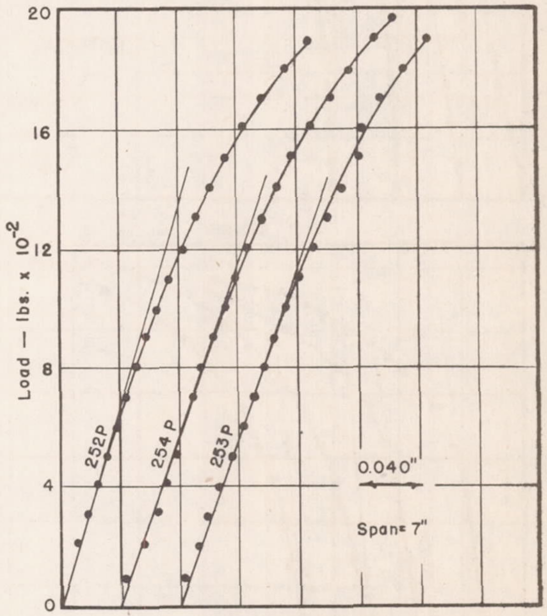
MATERIAL CL



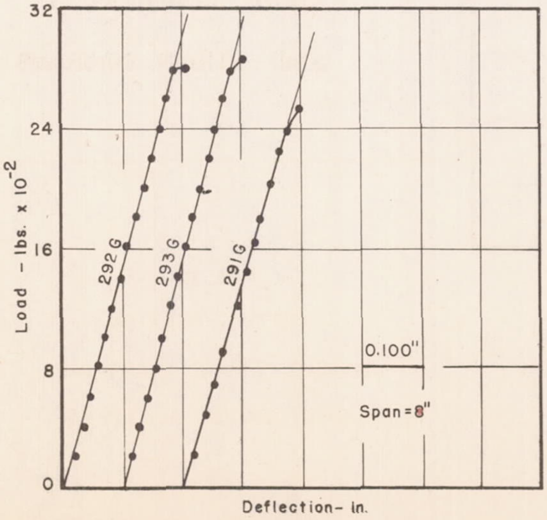
MATERIAL C



MATERIAL R



MATERIAL P

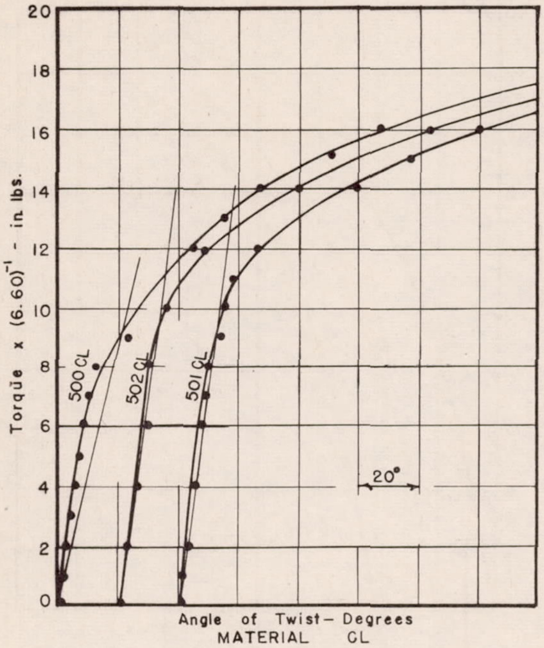


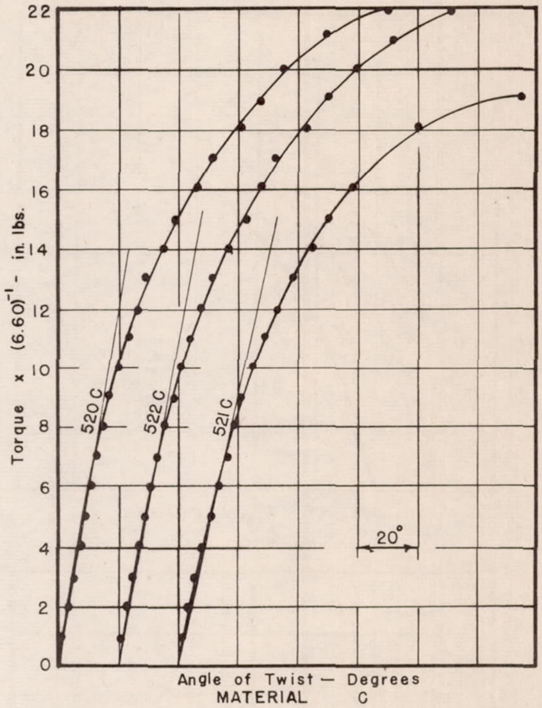
MATERIAL G

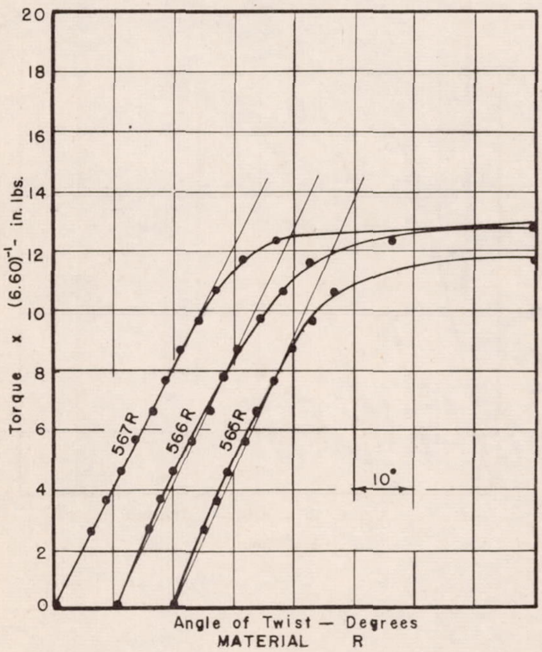
FIG. 14 —

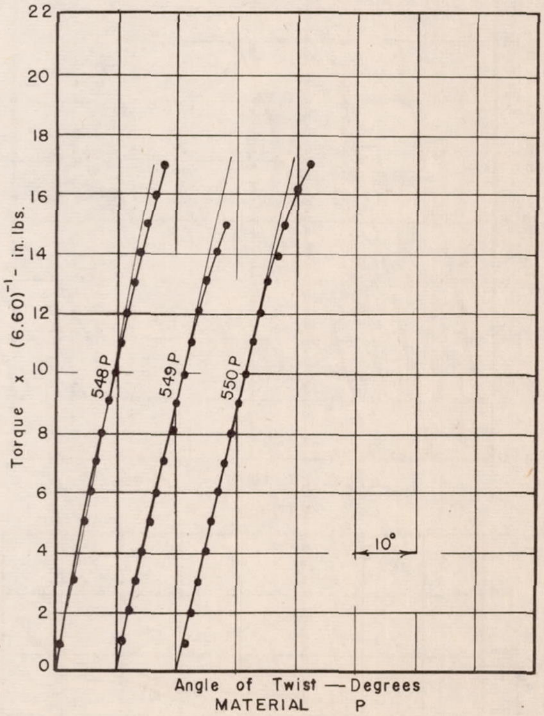
STATIC BENDING

LOAD - DEFLECTION DIAGRAMS









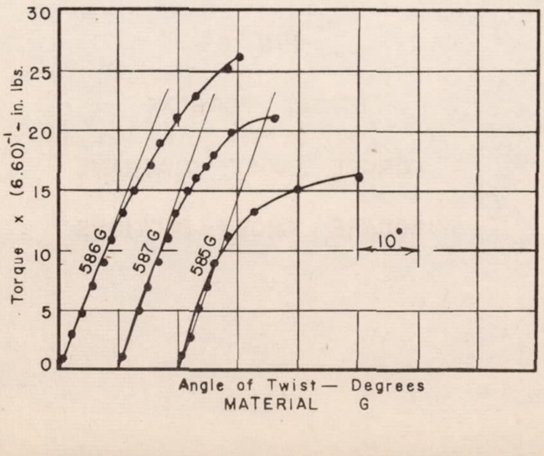
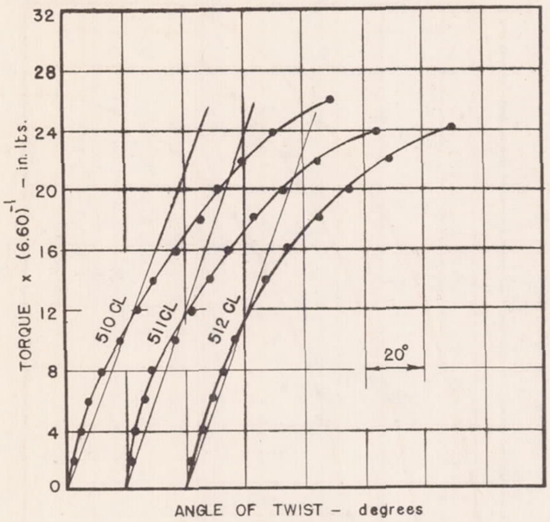


FIG. 15 —

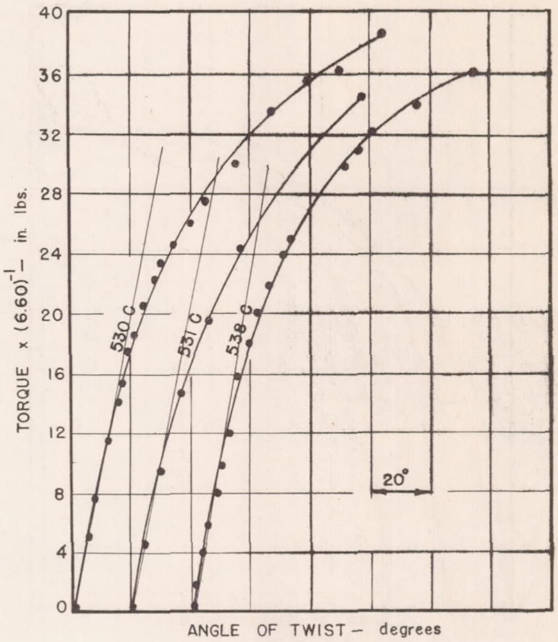
STATIC TORSION

TORQUE-TWIST DIAGRAMS

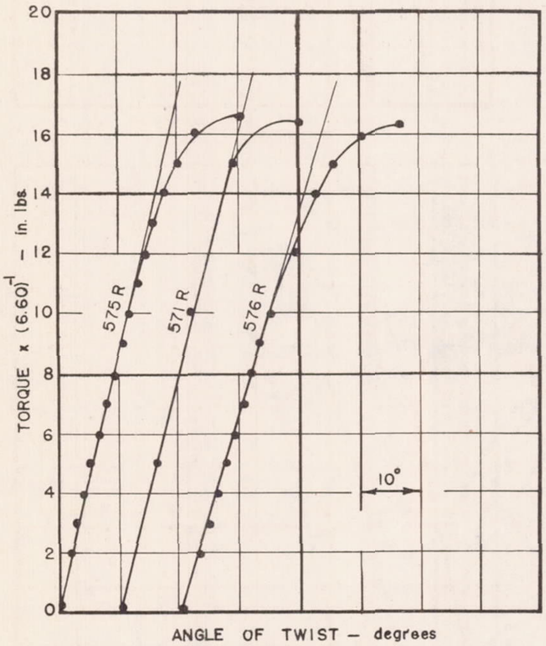
ROUND CROSS-SECTIONS



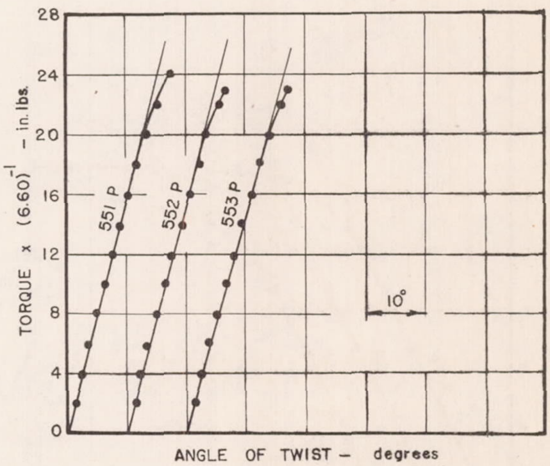
MATERIAL CL



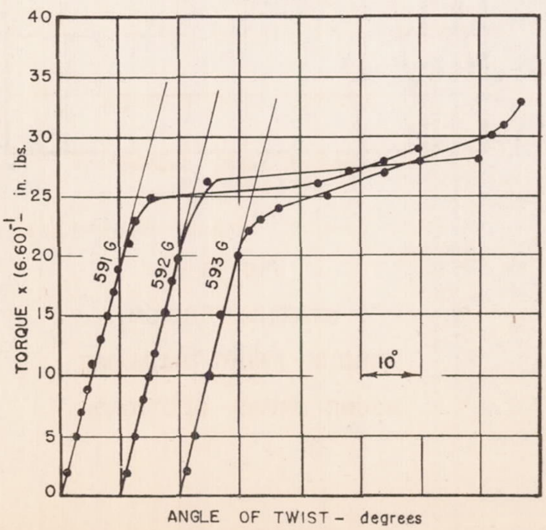
MATERIAL C



MATERIAL R



MATERIAL P



MATERIAL G

FIG. 16 –

STATIC TORSION

TORQUE - TWIST DIAGRAMS

SQUARE CROSS - SECTIONS

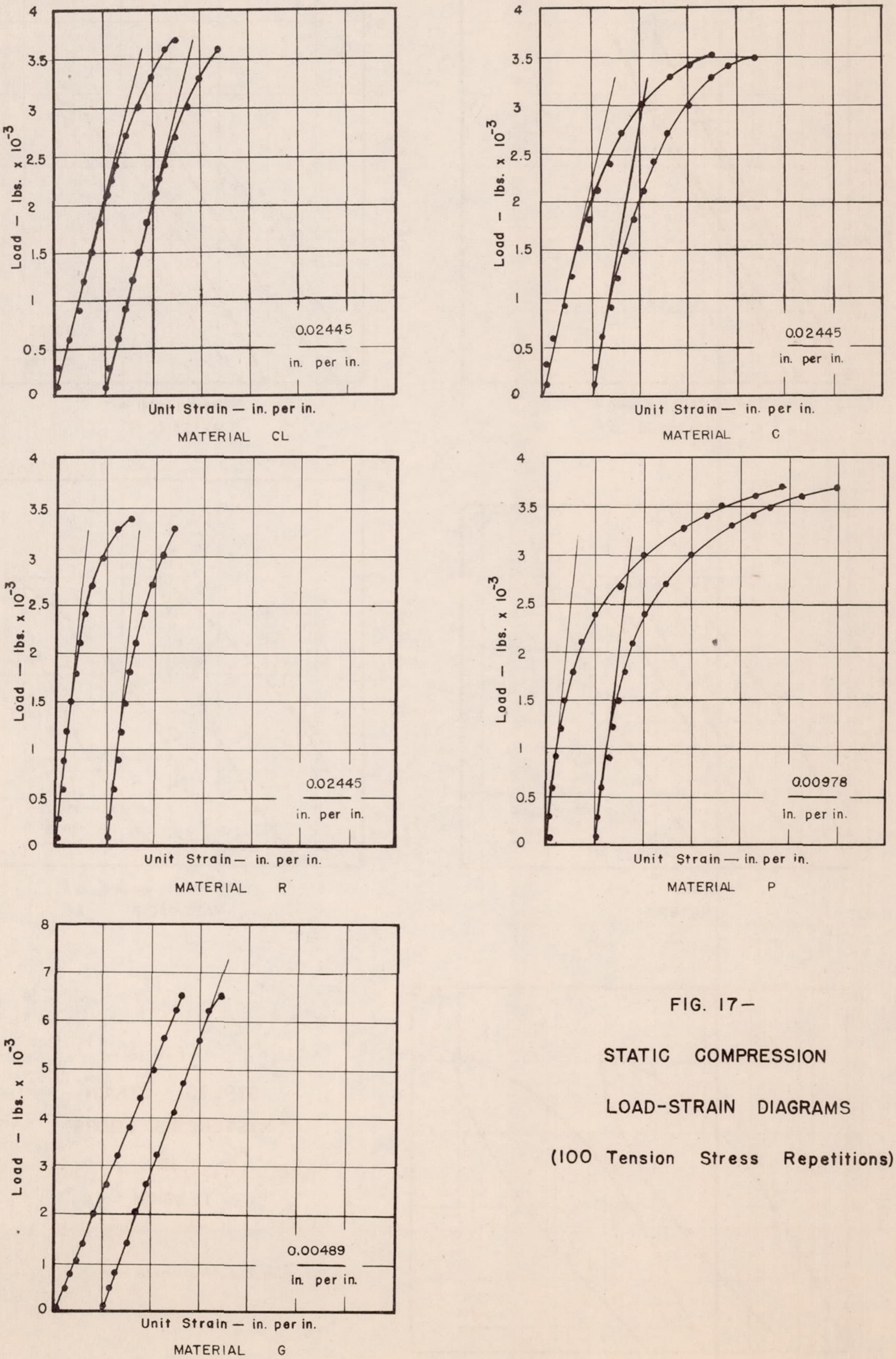
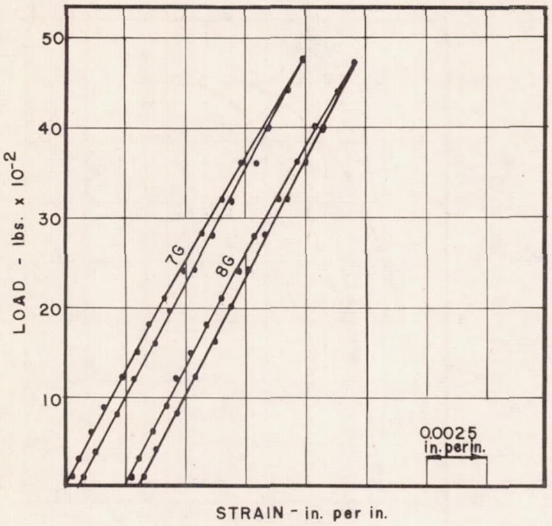


FIG. 17—

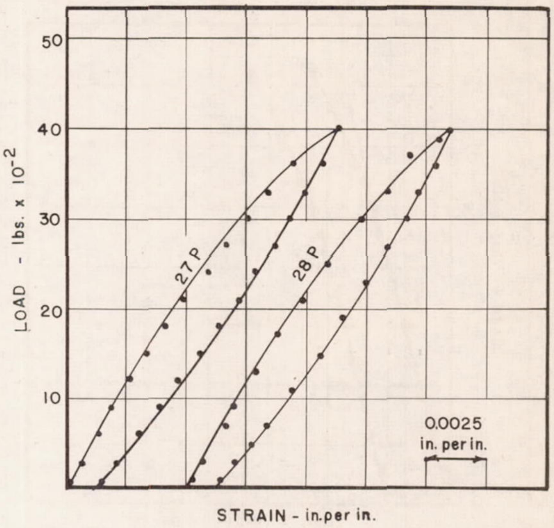
STATIC COMPRESSION

LOAD-STRAIN DIAGRAMS

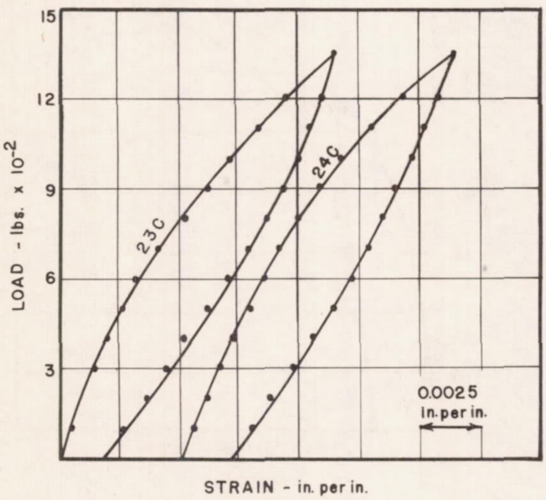
(100 Tension Stress Repetitions)



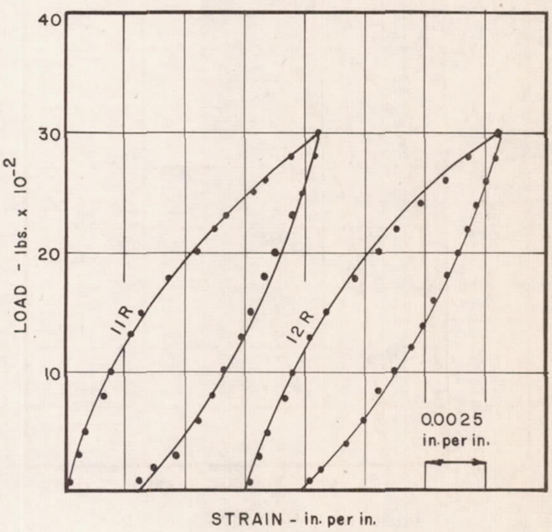
MATERIAL G



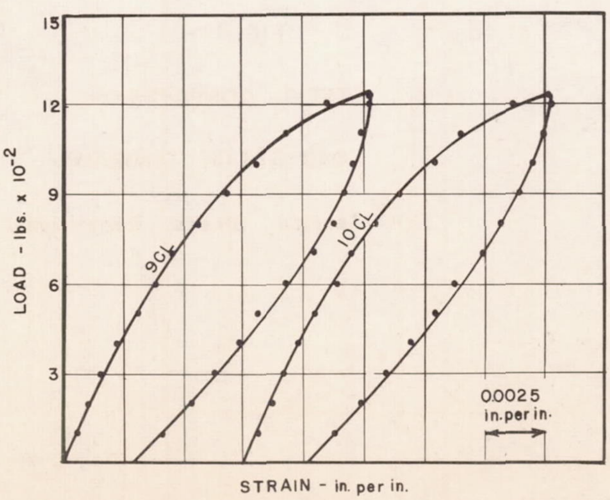
MATERIAL P



MATERIAL C



MATERIAL R



MATERIAL CL

FIG. 18 —

STRESS - STRAIN

HYSTERESIS LOOPS

IN

TENSION

Note: Maximum load = 2/3 ultimate load.

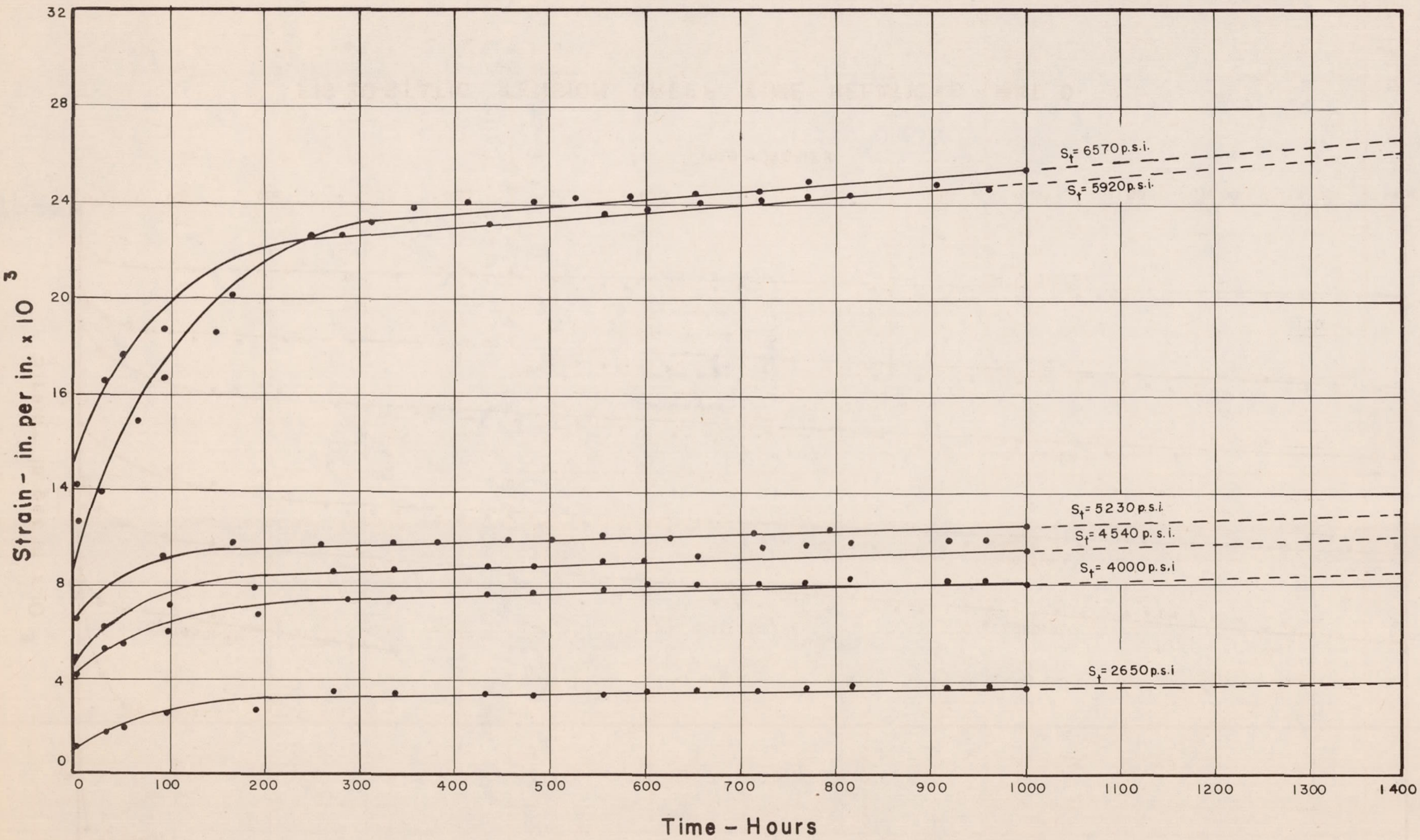


FIG.19-STATIC TENSION CREEP TIME RELATIONS- MAT. CL.

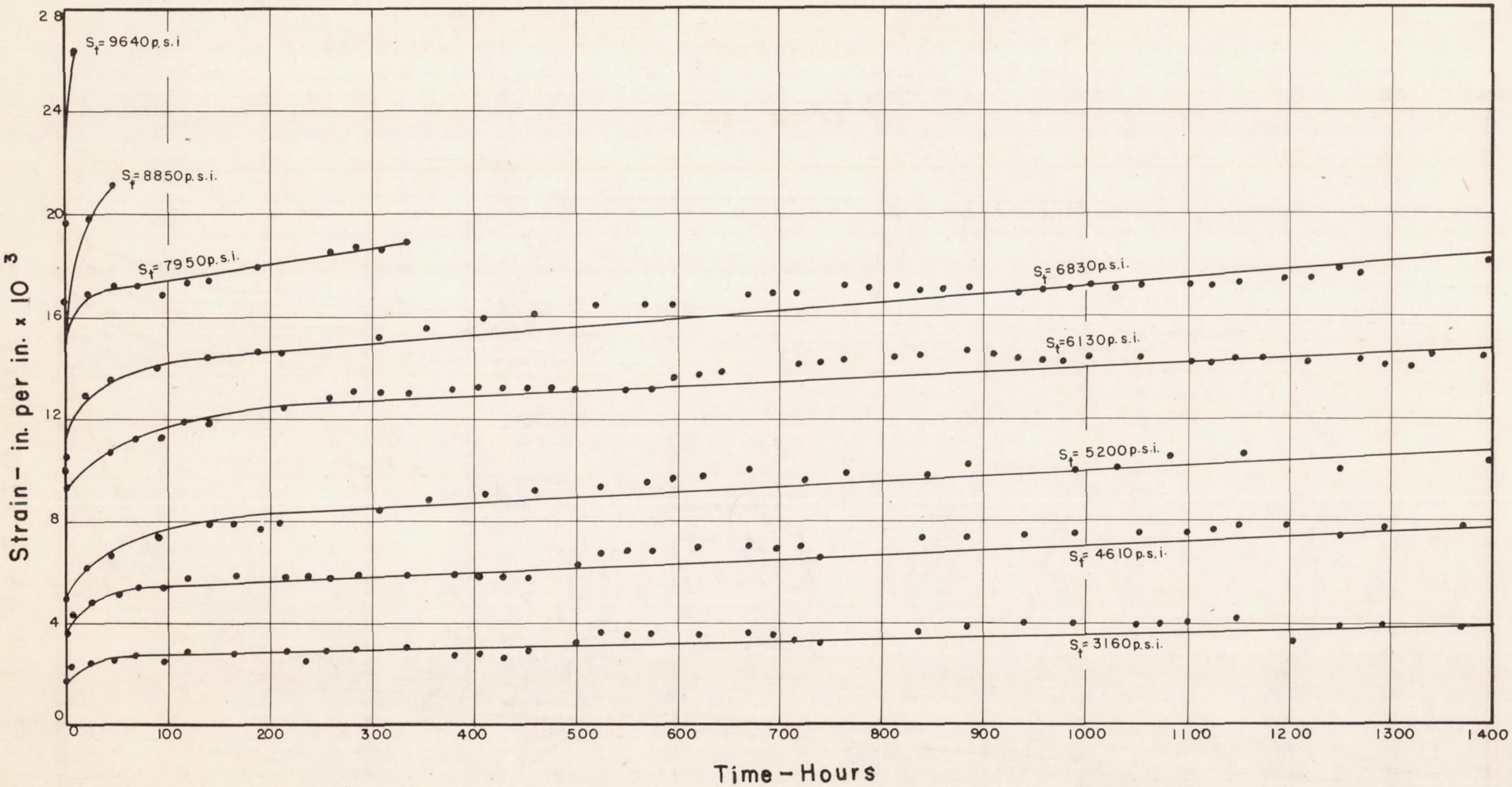


FIG. 20-STATIC TENSION CREEP TIME RELATIONS - MAT. C

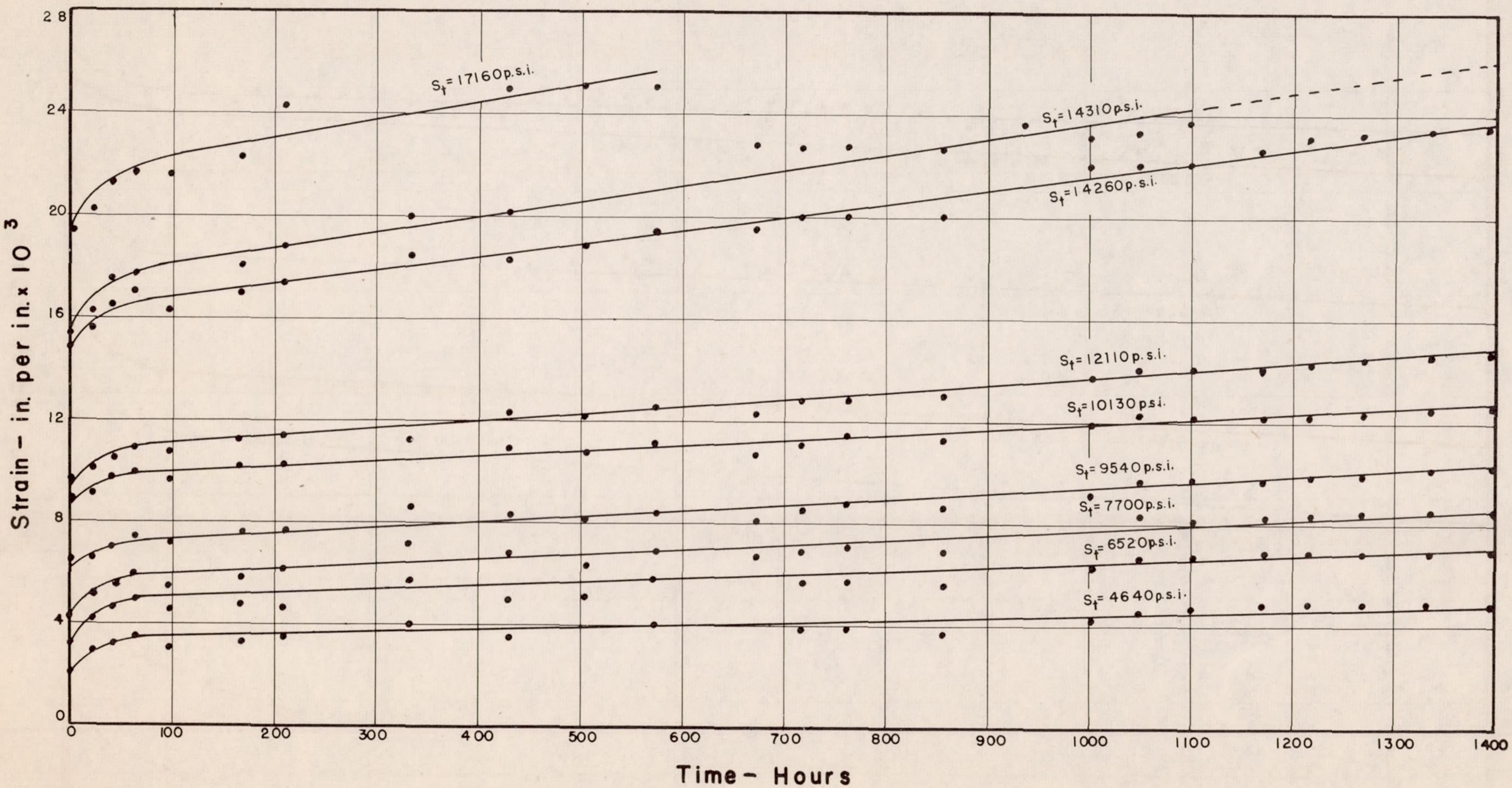


FIG.21-STATIC TENSION CREEP TIME RELATIONS - MAT. R

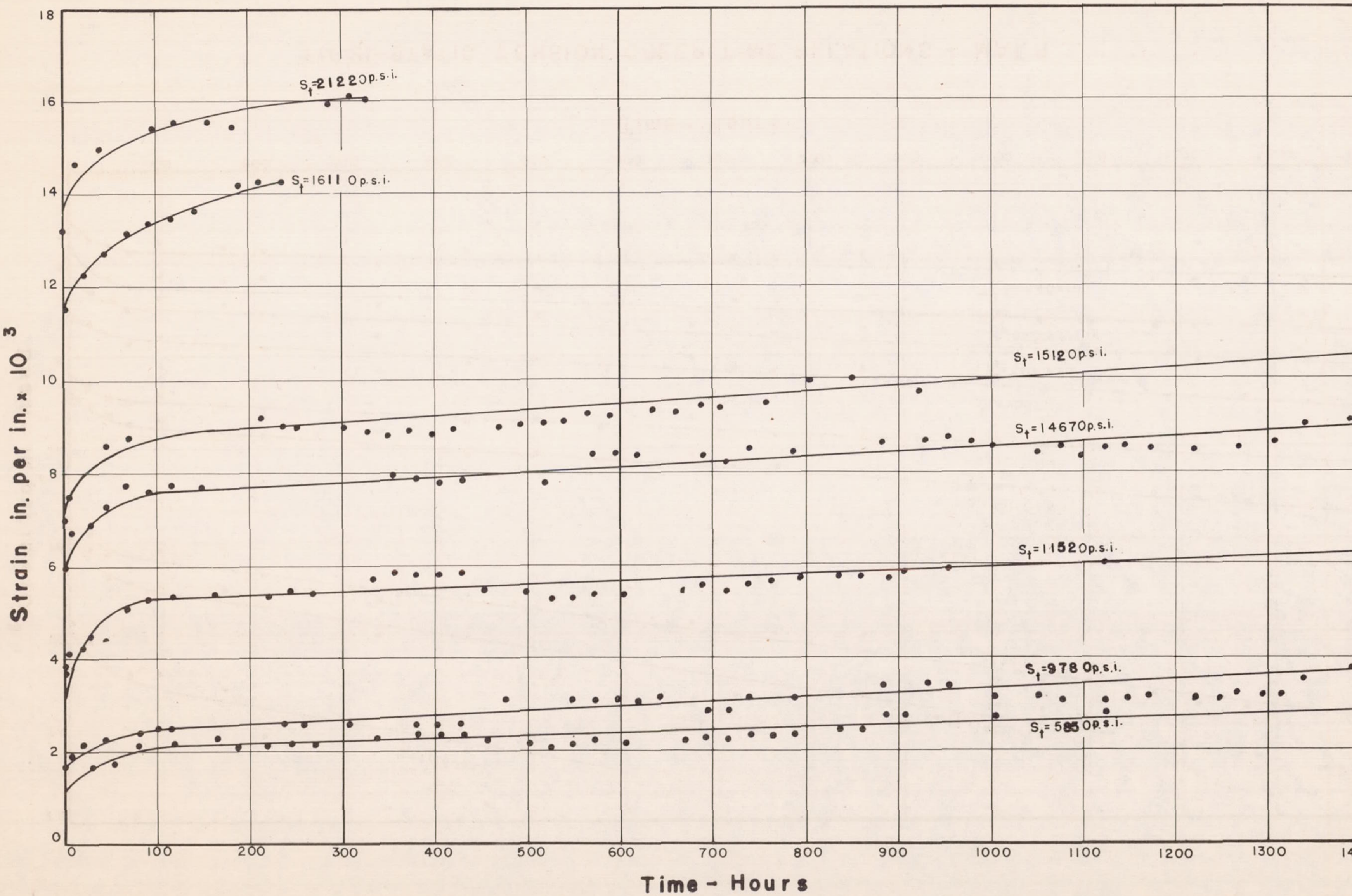


FIG. 22-STATIC TENSION CREEP TIME RELATIONS - MAT. P

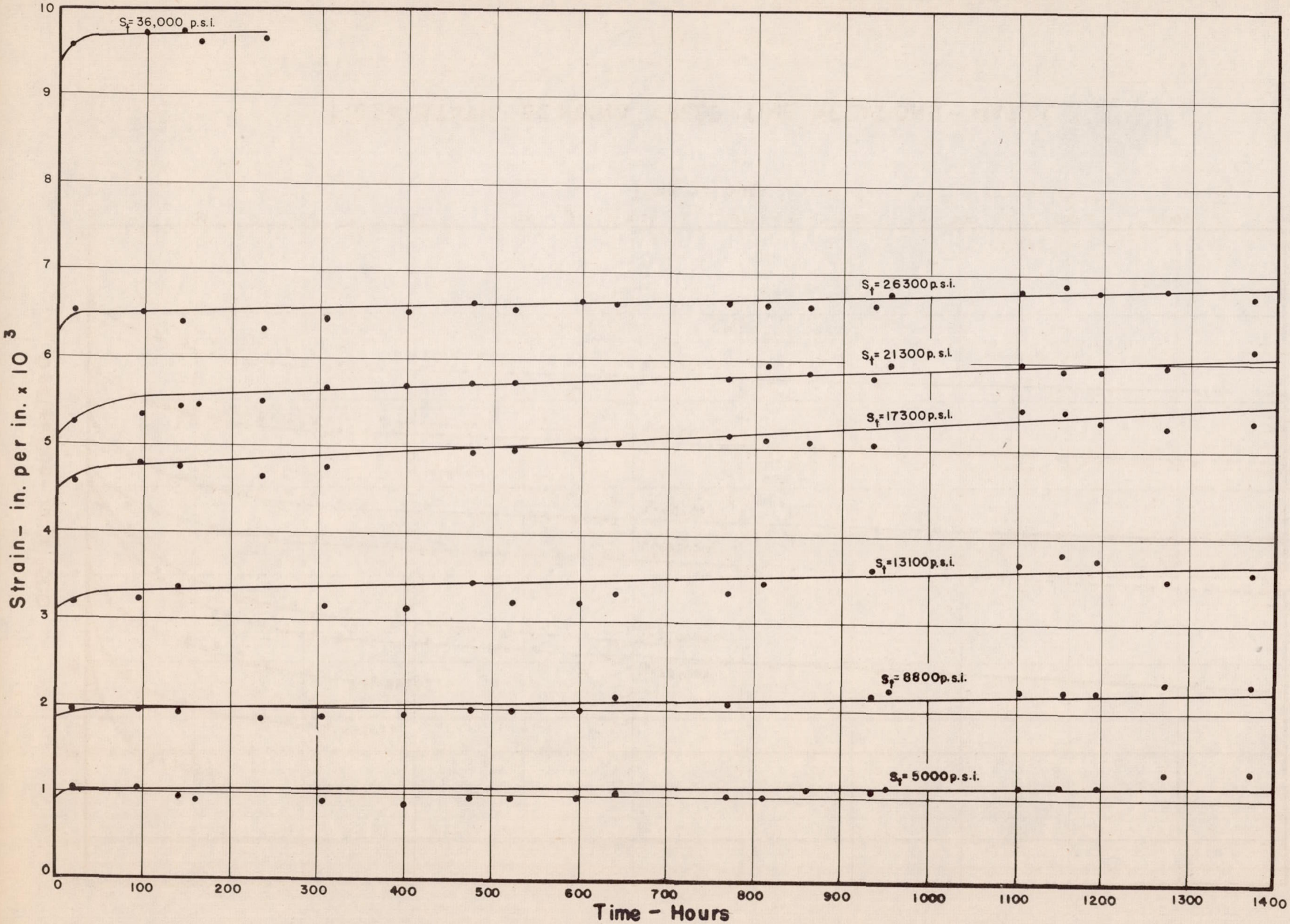


FIG.23-STATIC TENSION CREEP TIME RELATIONS- MAT. G

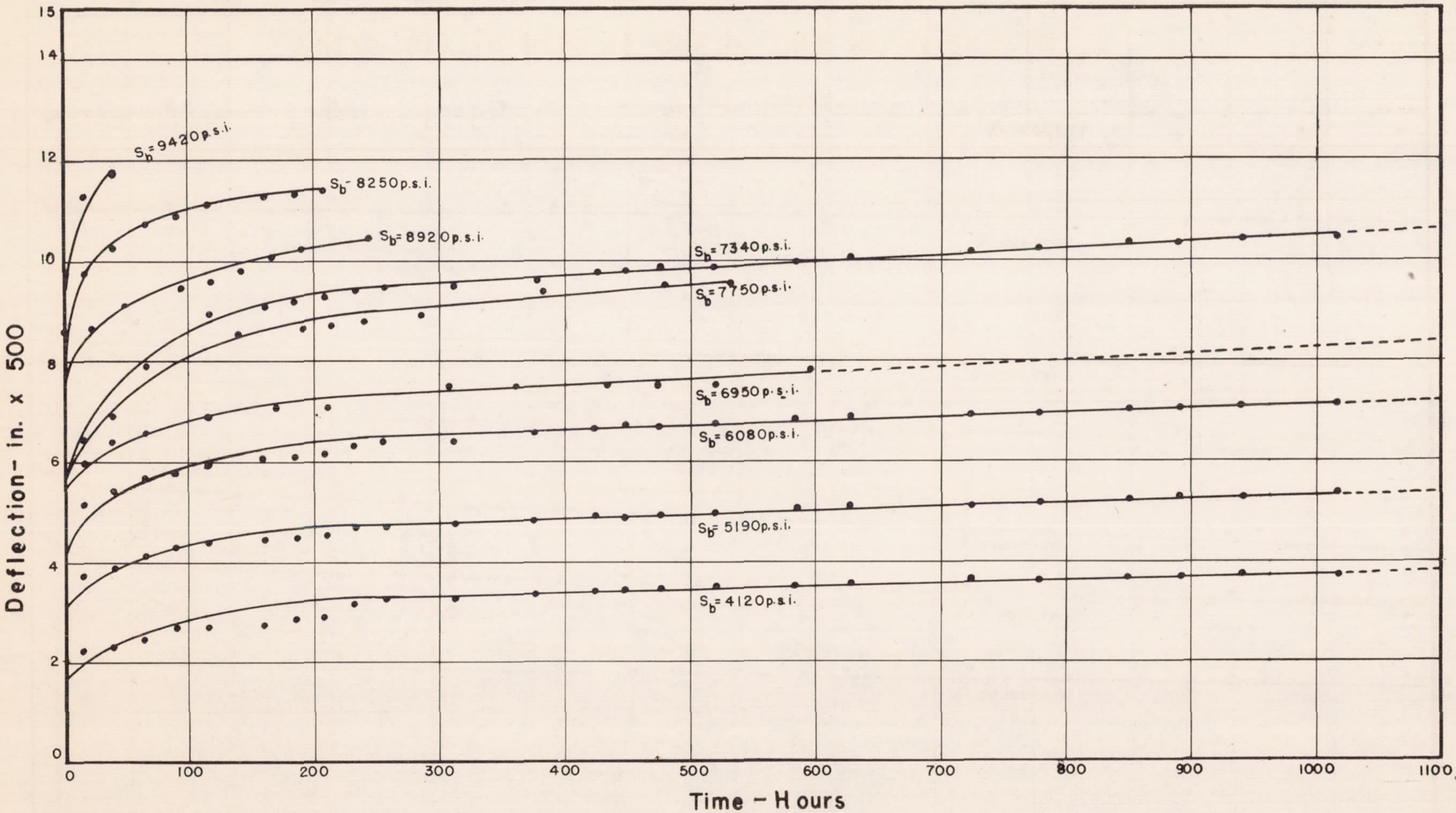


FIG.24-STATIC BENDING CREEP TIME RELATIONS - MAT. CL

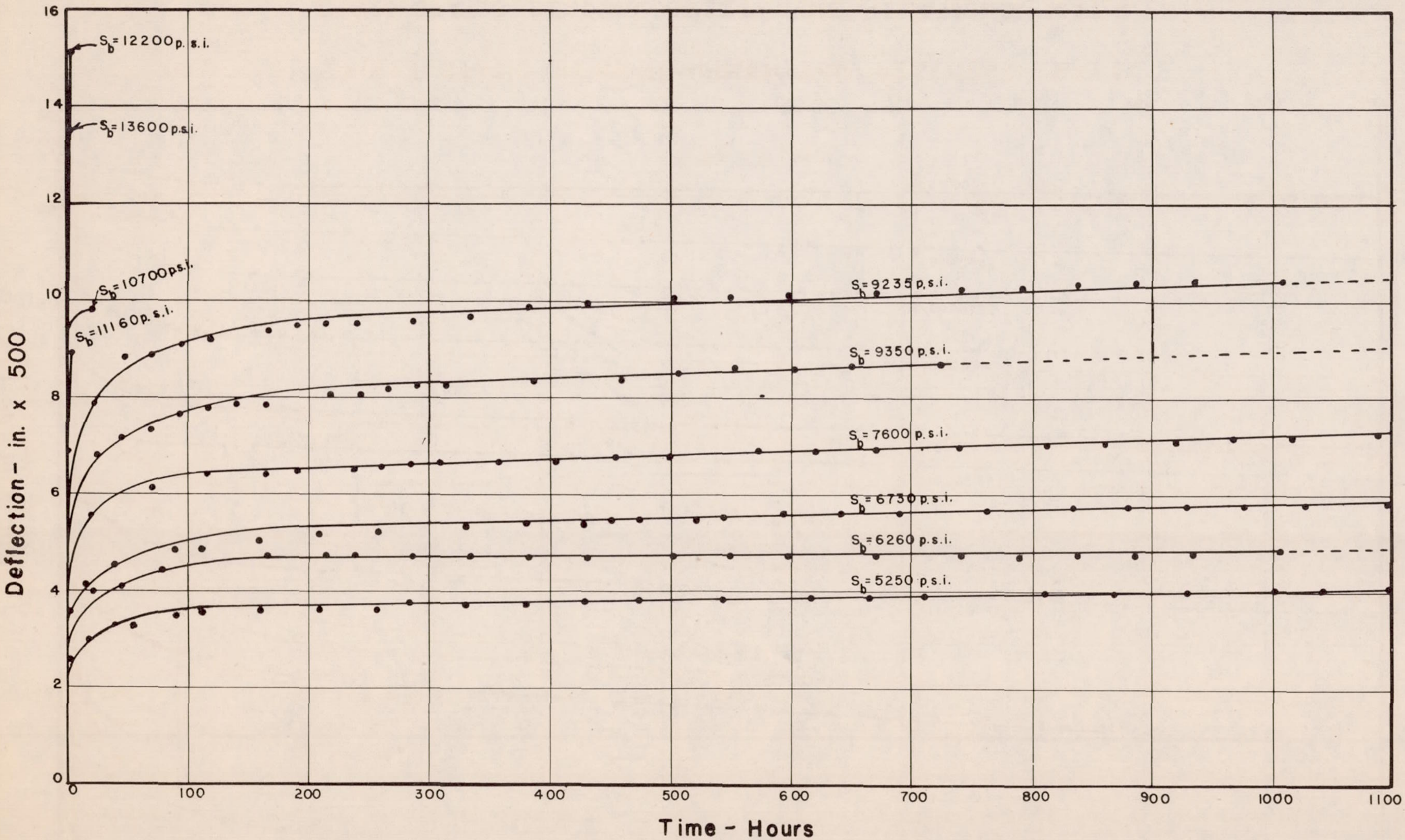


FIG.25- STATIC BENDING CREEP TIME RELATIONS - MAT. C

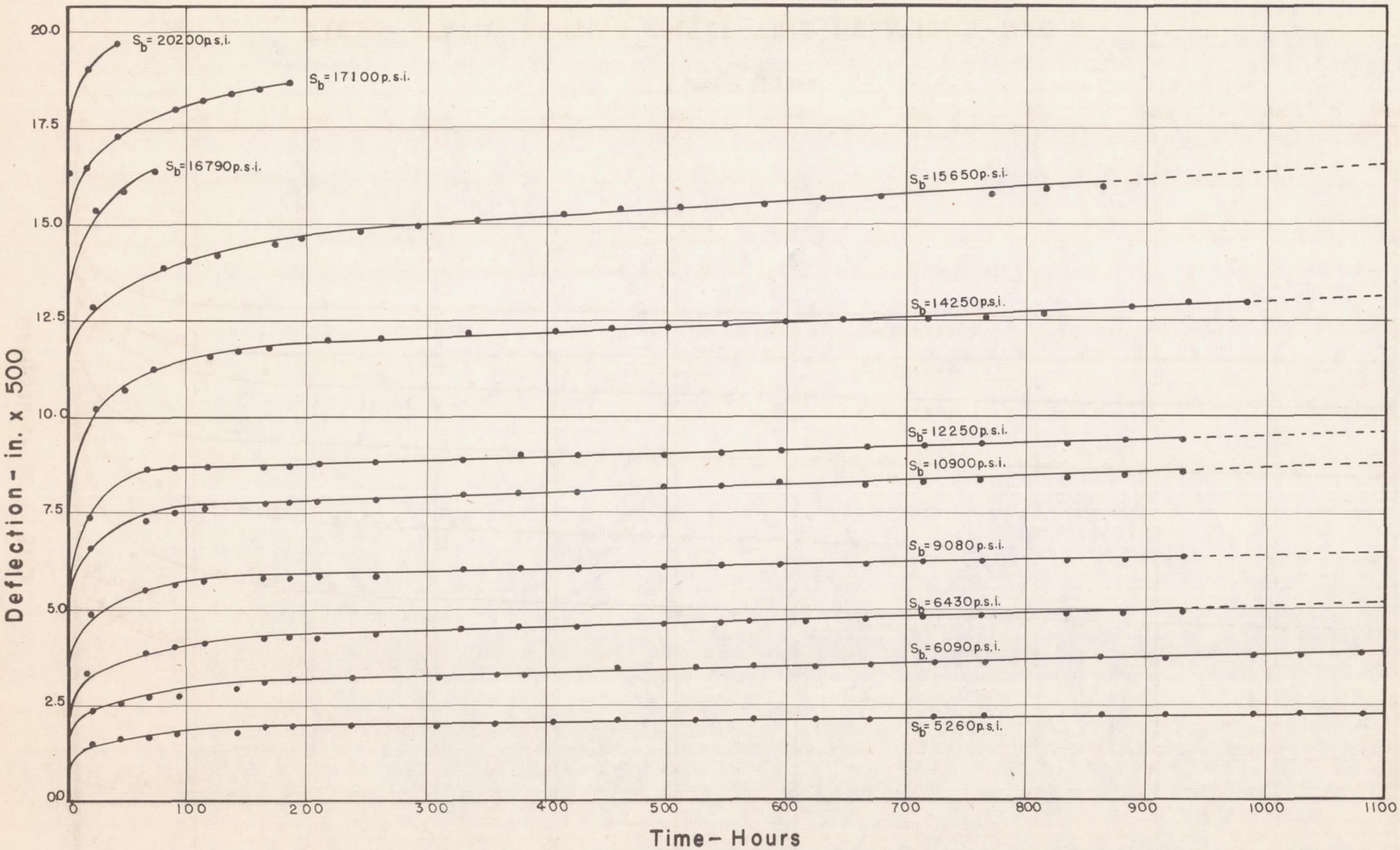


FIG.26-STATIC BENDING CREEP TIME RELATIONS - MAT. R

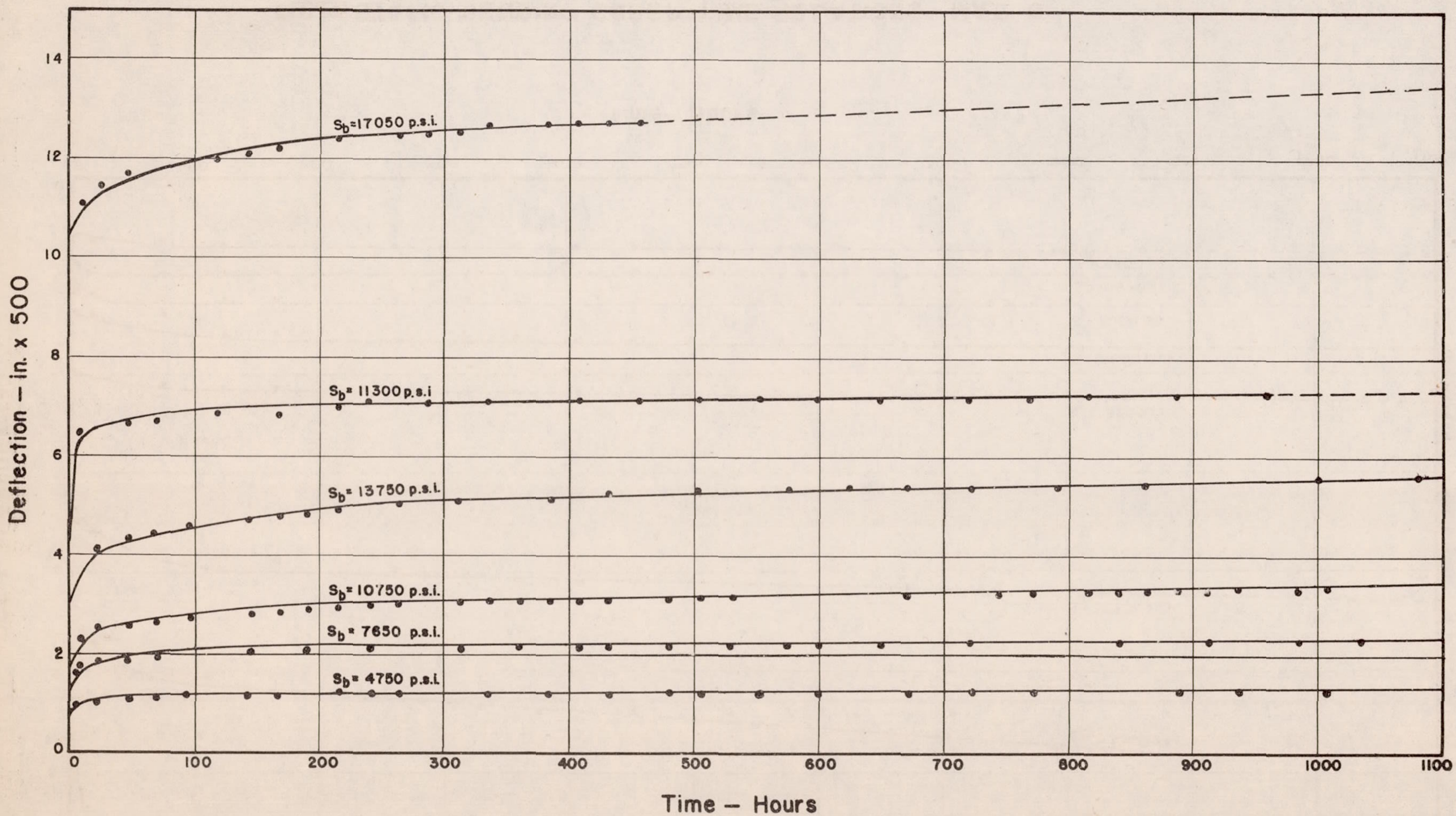


FIG. 27.– STATIC BENDING CREEP TIME RELATIONS – MAT. P

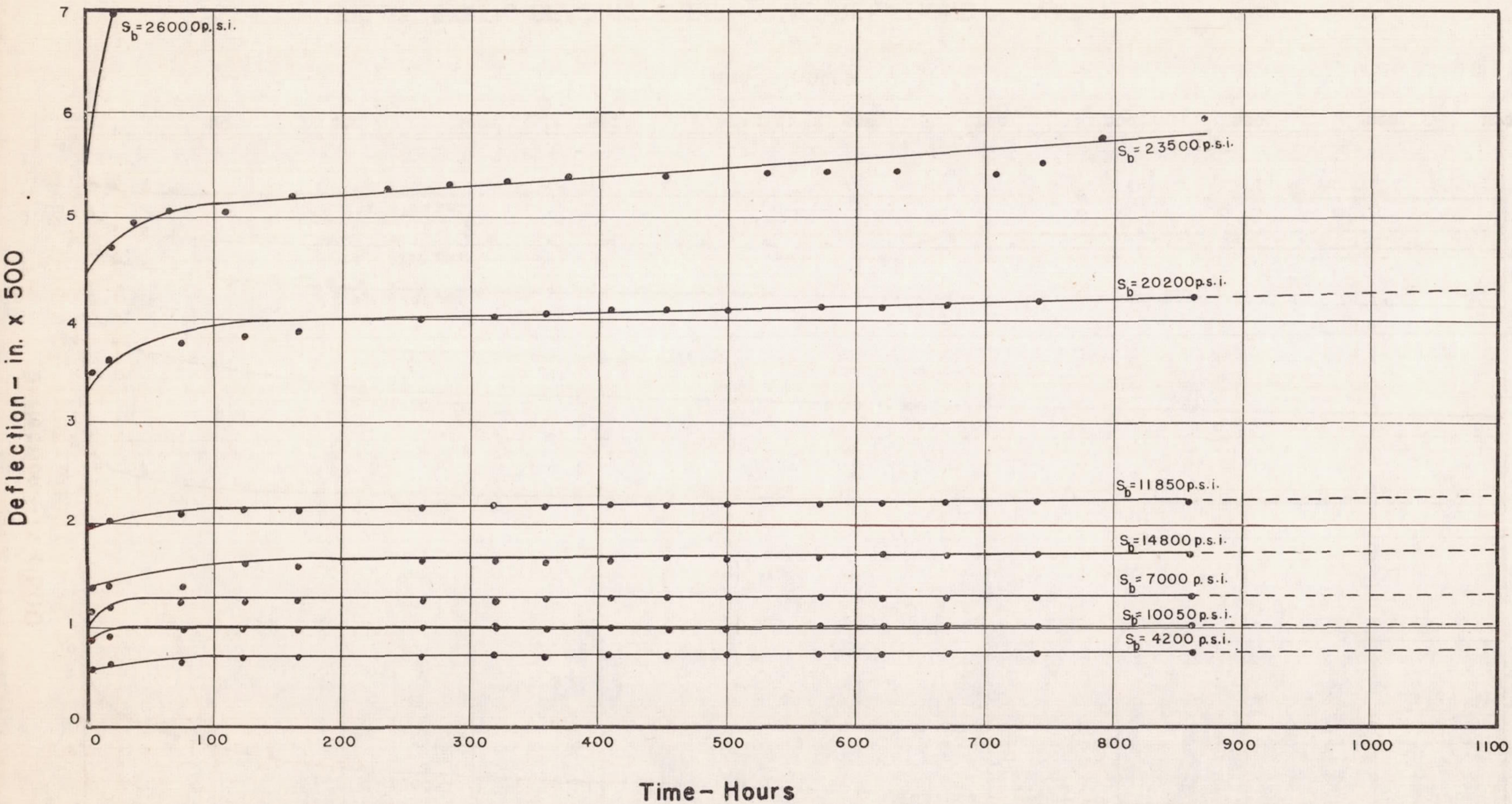


FIG.28-STATIC BENDING CREEP TIME RELATIONS - MAT. G

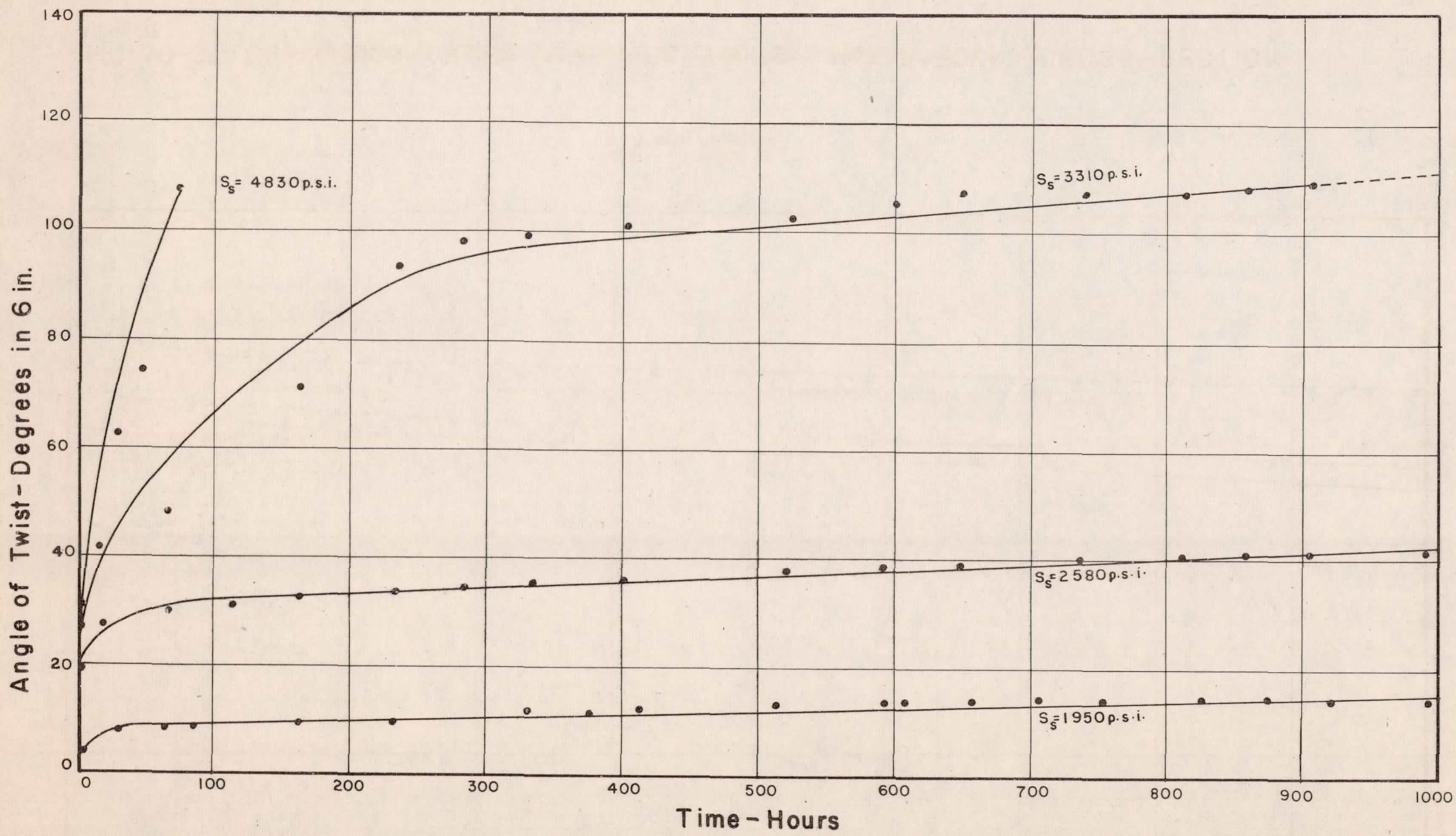


FIG.29-STATIC TORSION CREEP TIME RELATIONS MAT. R- ROUND CROSS-SECTION

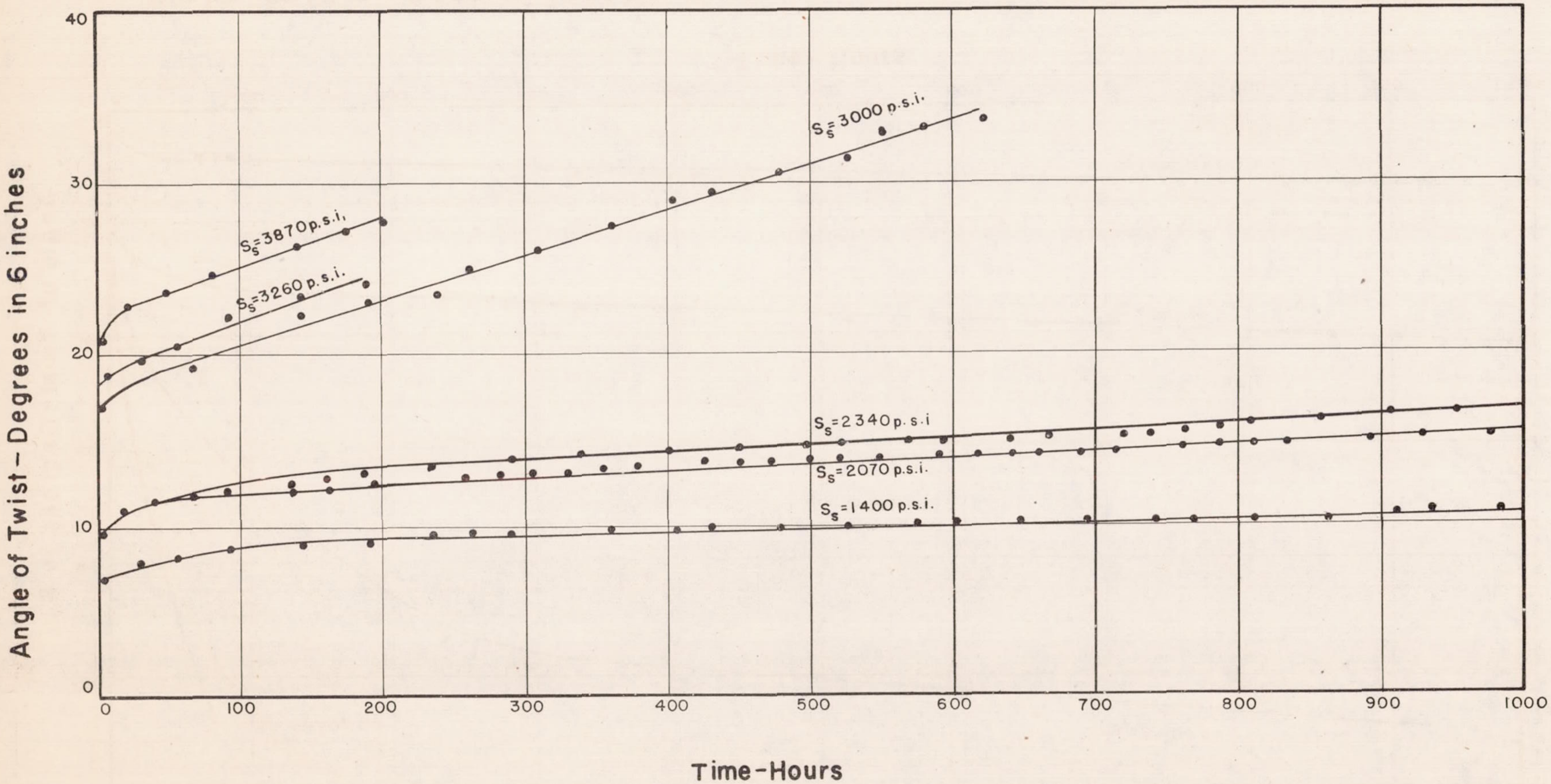


FIG. 30-STATIC TORSION CREEP TIME RELATIONS - MAT. P-ROUND CROSS-SECTION

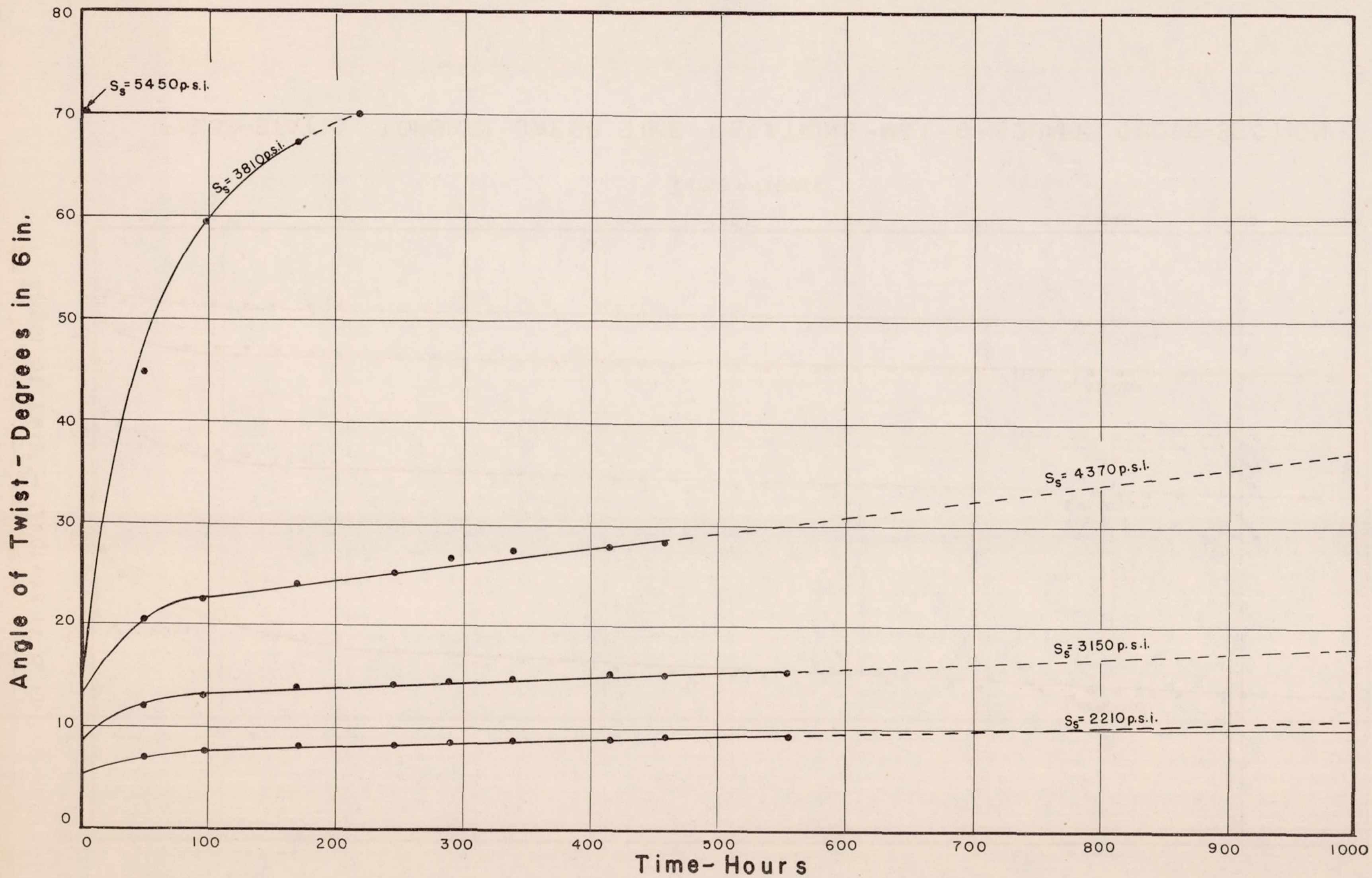


FIG. 31 – STATIC TORSION CREEP TIME RELATIONS - MAT. G - ROUND CROSS-SECTION

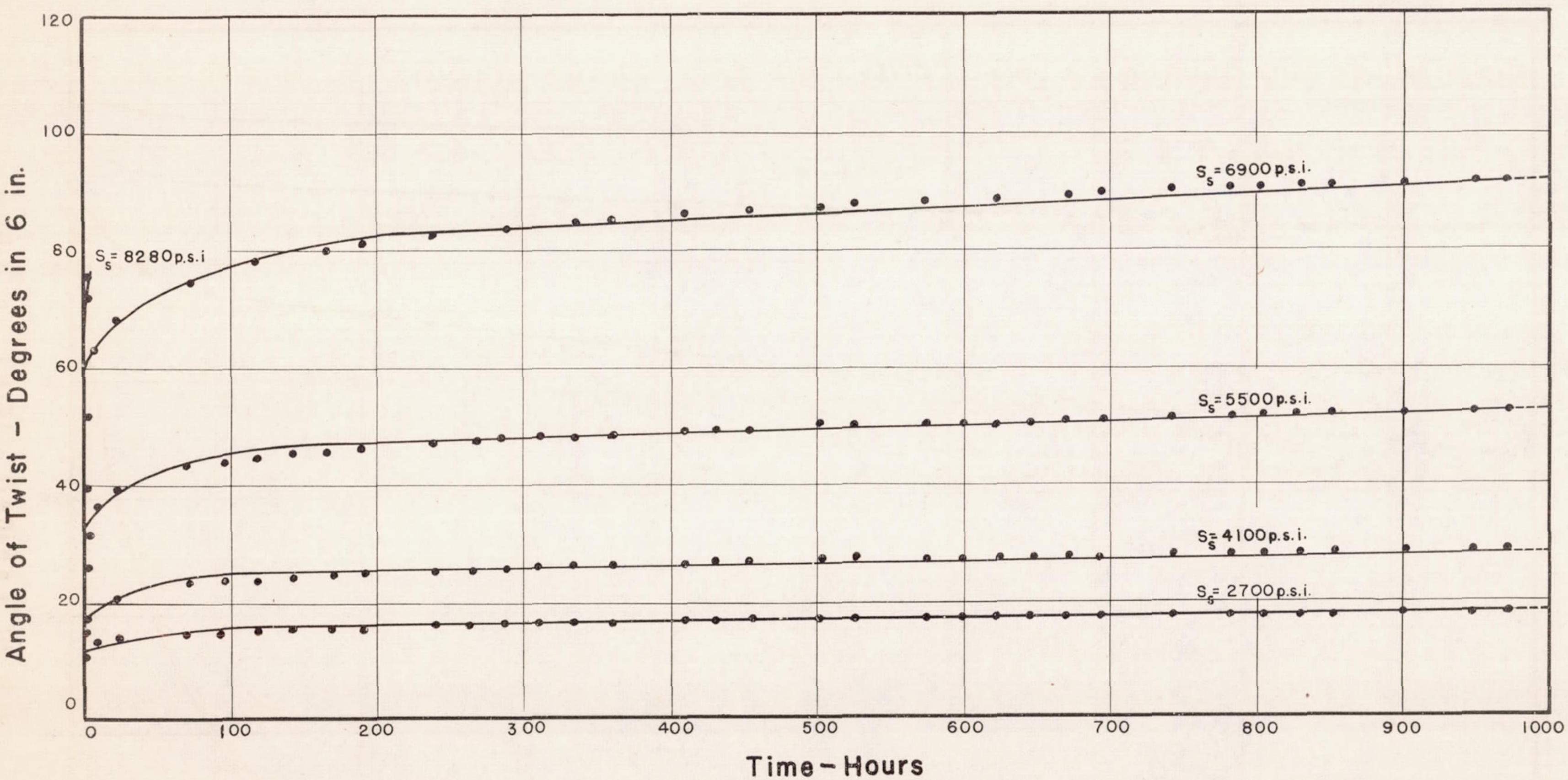


FIG. 32-STATIC TORSION CREEP TIME RELATIONS-MAT. C-SQUARE CROSS-SECTION

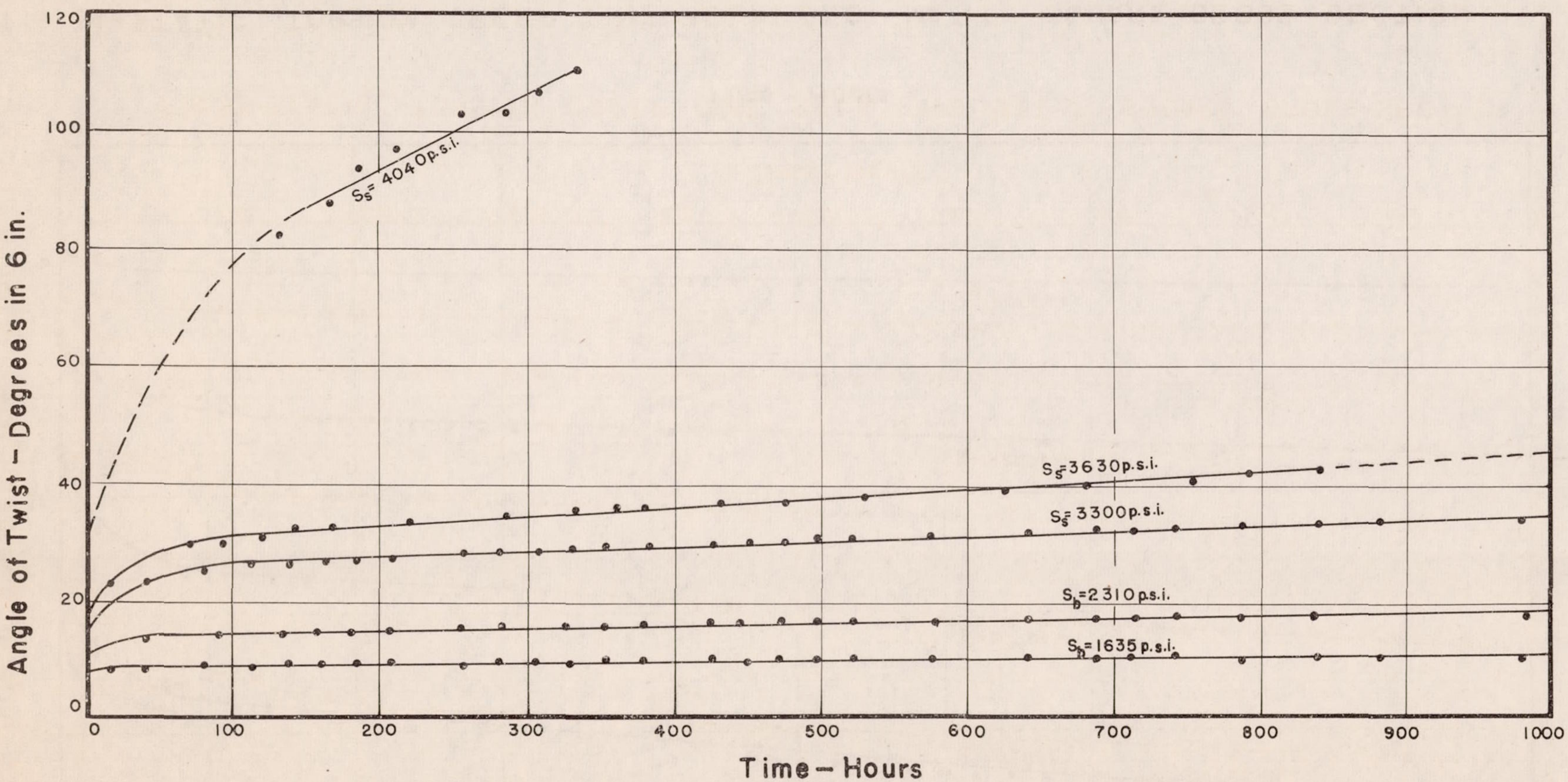


FIG. 33-STATIC TORSION CREEP TIME RELATIONS - MAT. R - SQUARE CROSS-SECTION

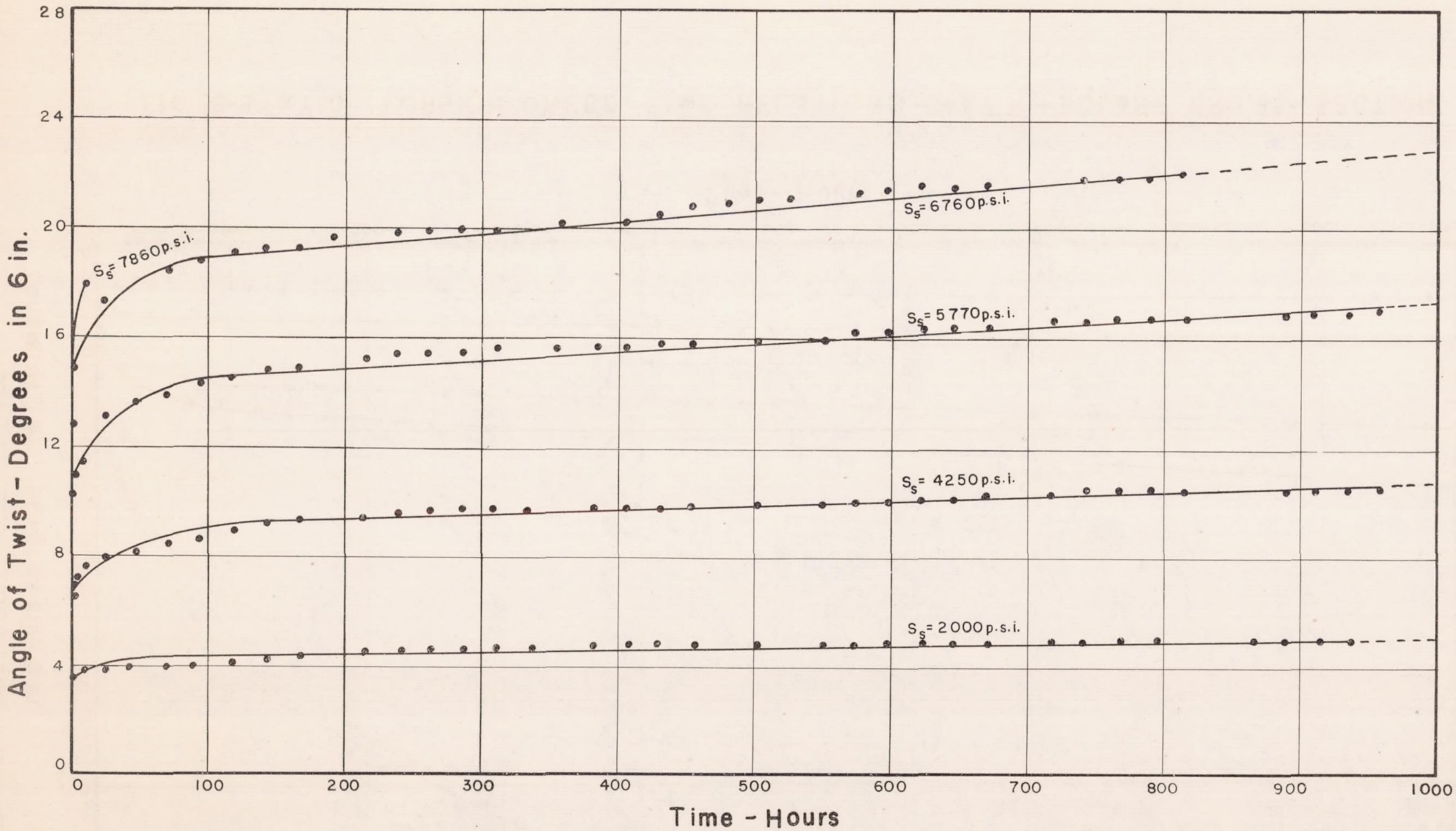


FIG. 34-STATIC TORSION CREEP TIME RELATIONS- MAT. P- SQUARE CROSS-SECTION

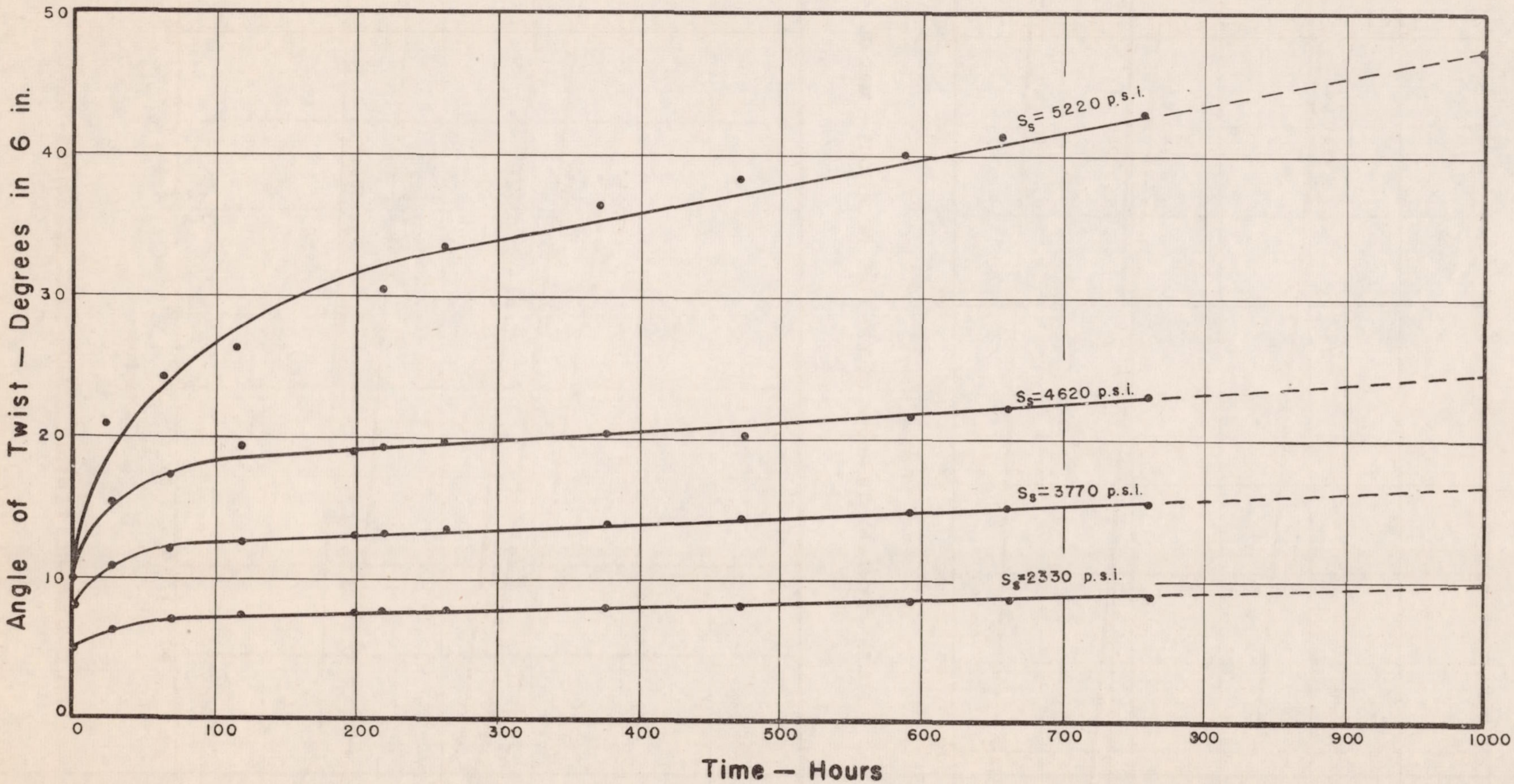


FIG. 35-STATIC TORSION CREEP TIME RELATIONS - MAT. G - SQUARE CROSS-SECTION

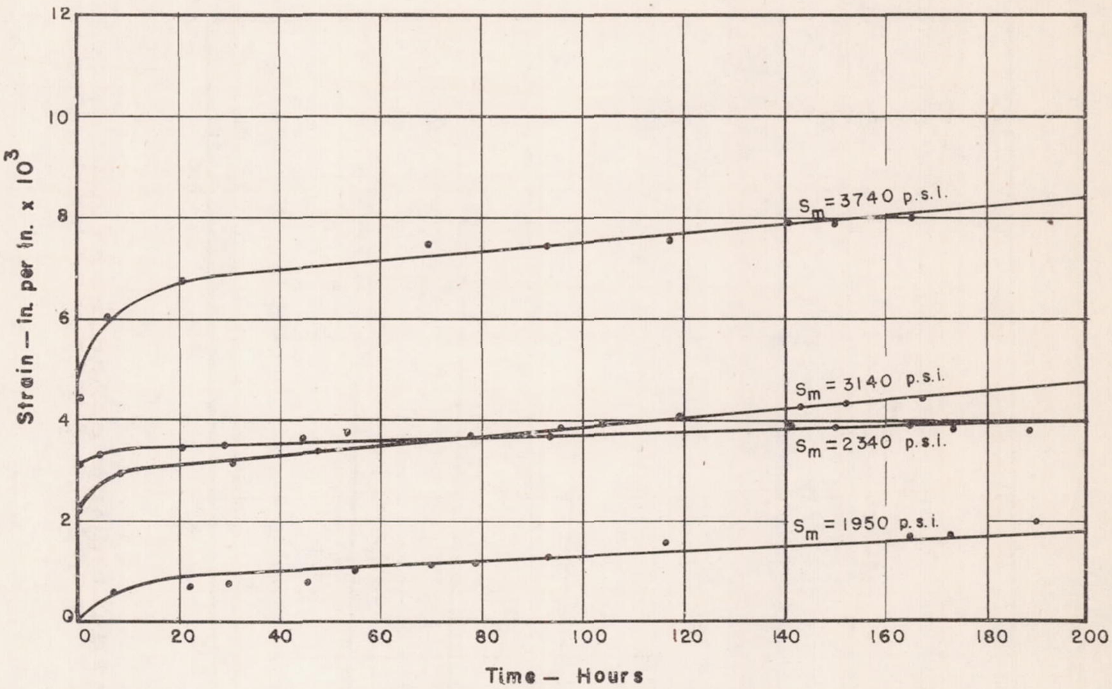


FIG.36 - DYNAMIC TENSION CREEP-TIME RELATIONS - MAT. CL

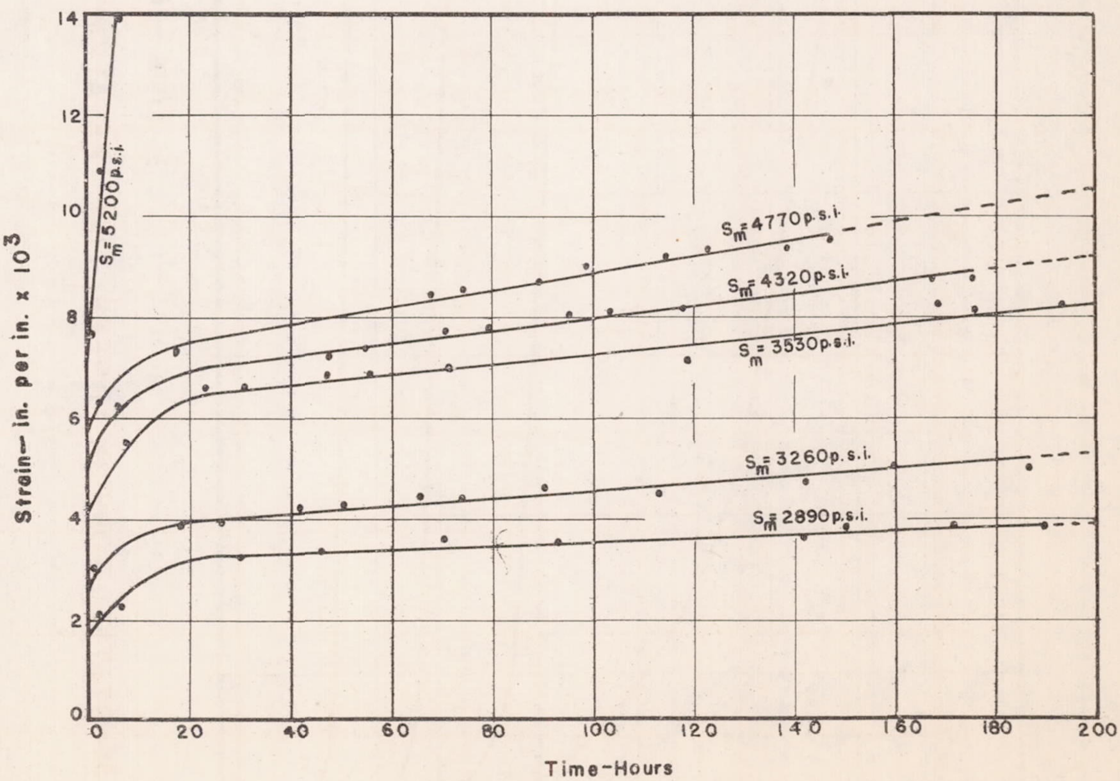


FIG.37-DYNAMIC TENSION CREEP-TIME RELATIONS-MAT.C

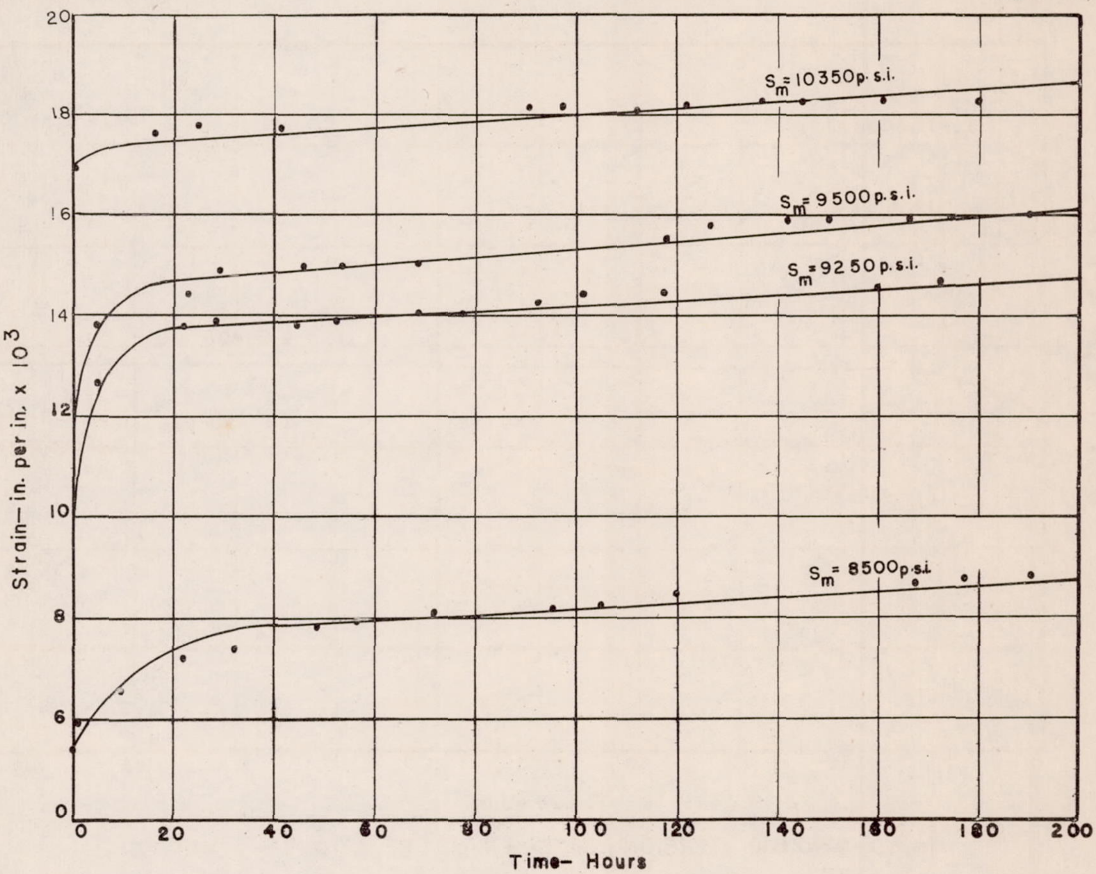


FIG. 38 - DYNAMIC TENSION CREEP-TIME RELATIONS – MAT. R

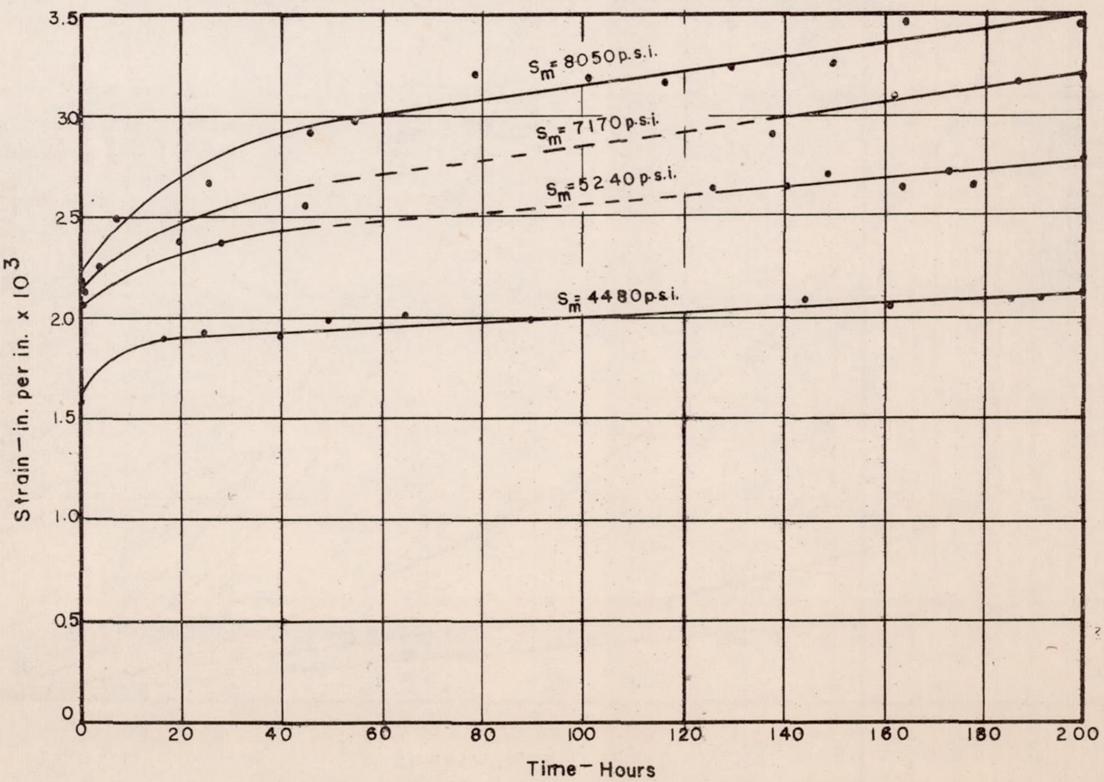


FIG. 39 - DYNAMIC TENSION CREEP-TIME RELATIONS – MAT. P

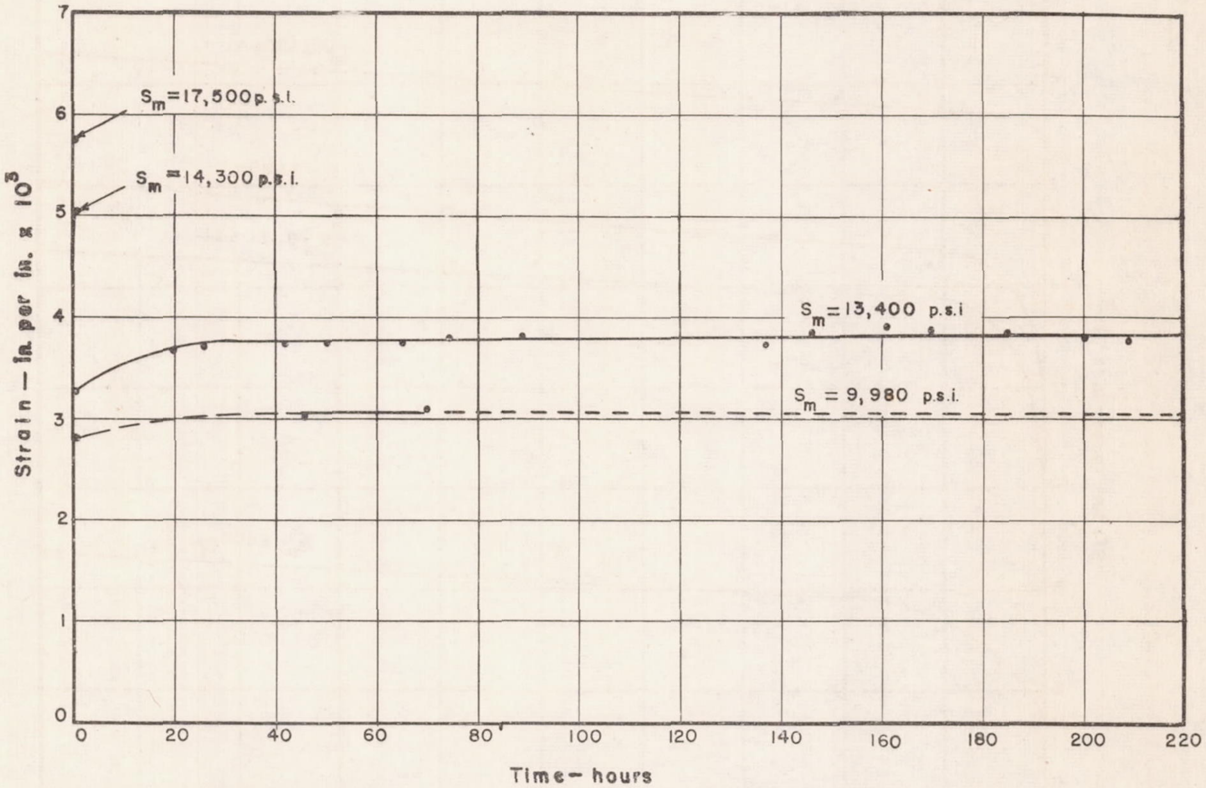


FIG. 40-DYNAMIC TENSION CREEP-TIME RELATIONS— MAT. G

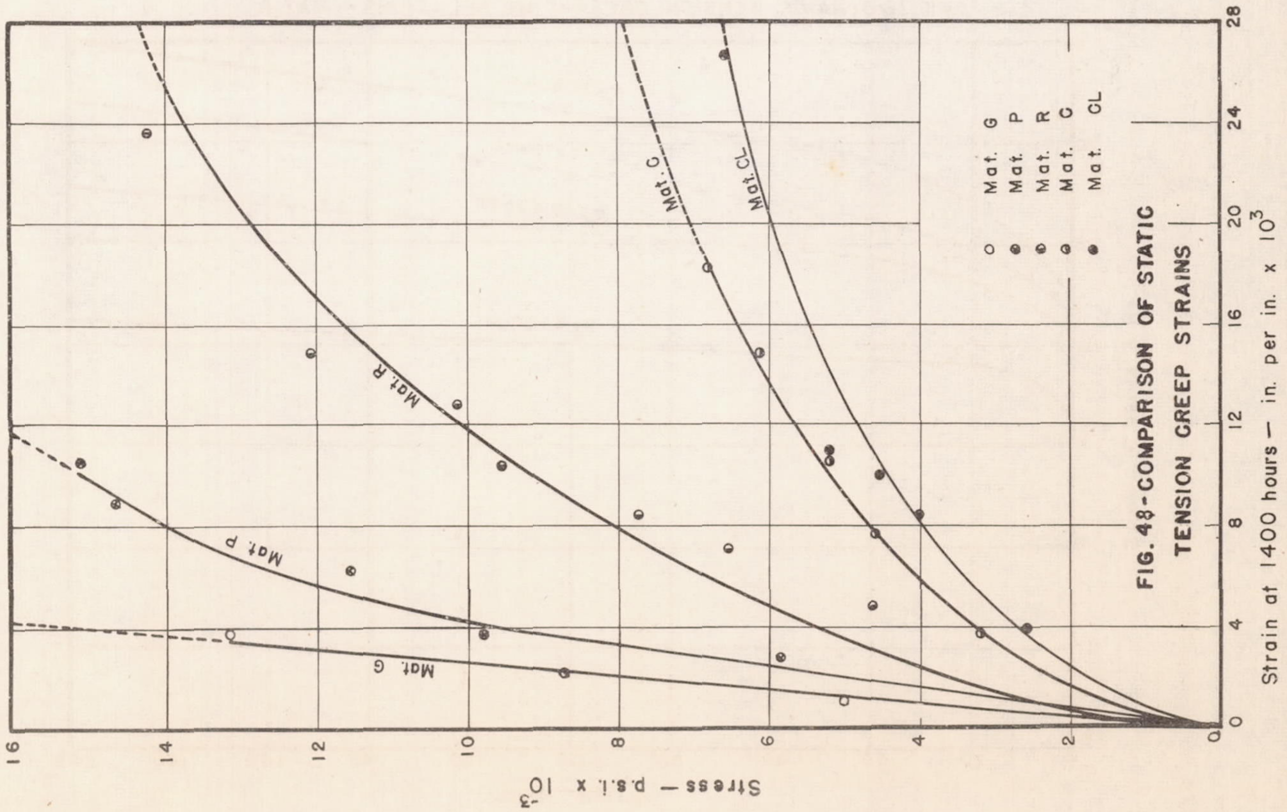


FIG. 48-COMPARISON OF STATIC TENSION CREEP STRAINS

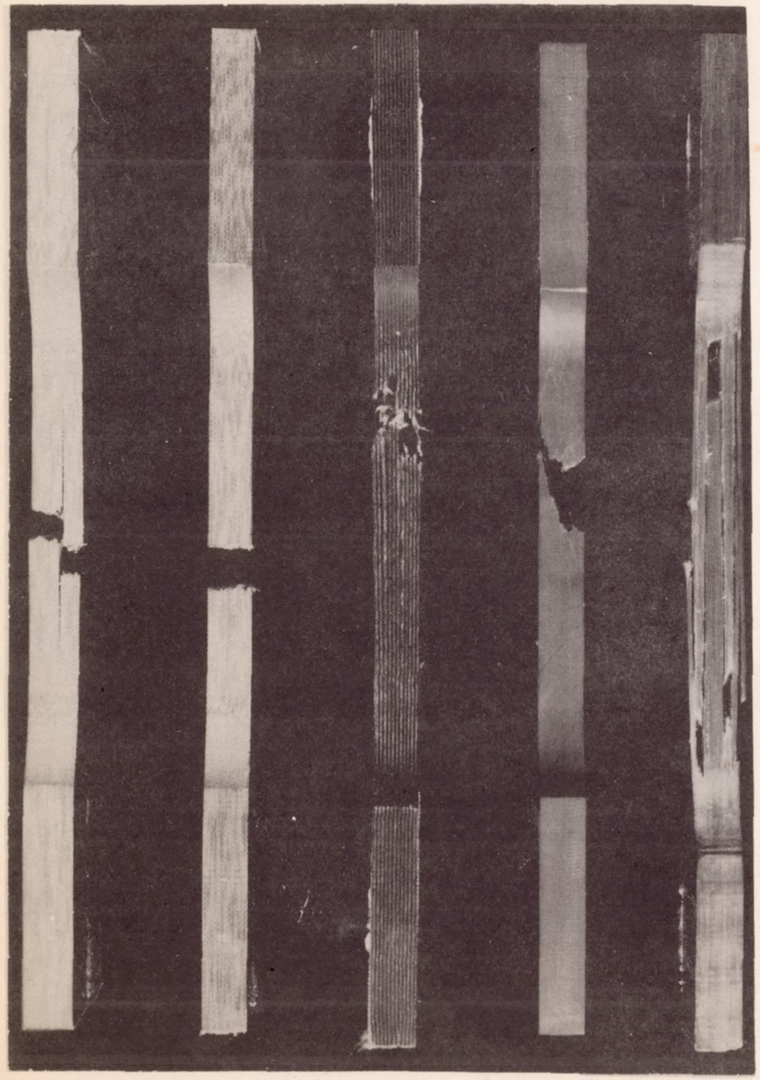


Figure 41.- Static tension specimens showing type of fracture; left to right, materials CL, C, R, P and G.

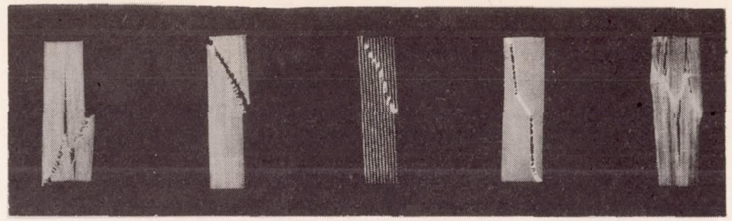


Figure 42.- Static compression specimens showing type of fracture; left to right, materials CL, C, R, P and G.

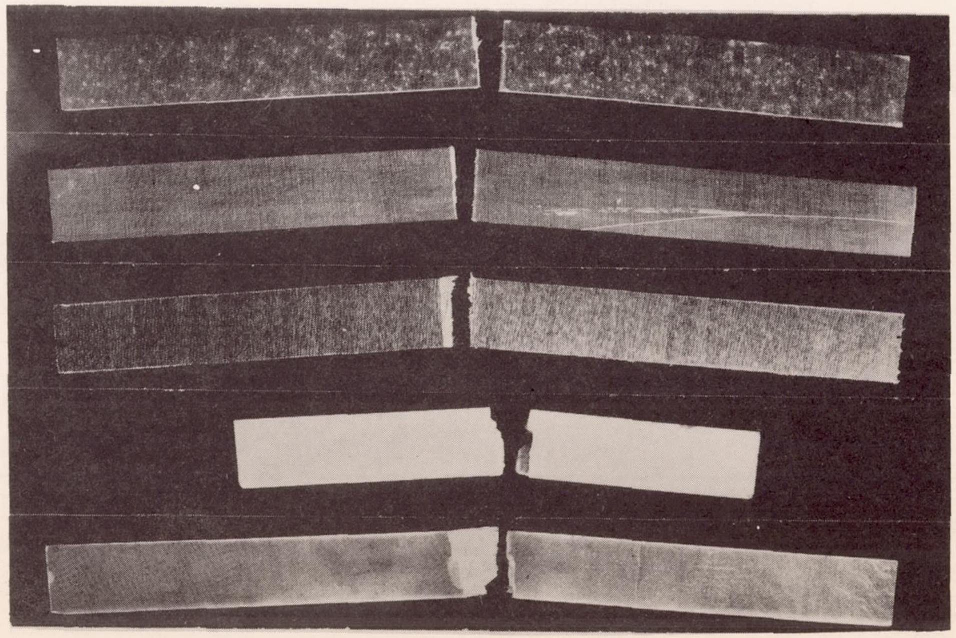


Figure 43.- Static bending specimens showing type of fracture; top to bottom, materials CL, C, R, P and G.

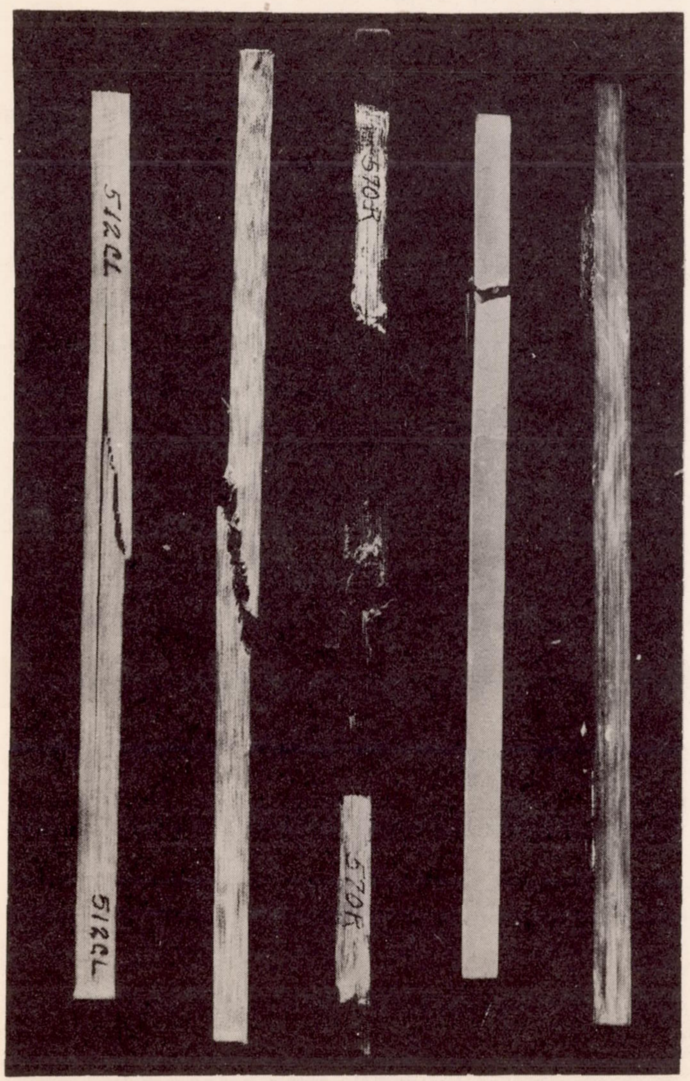


Figure 44.- Static torsion specimens showing type of fracture, square cross-sections; left to right, materials CL, C, R, P and G.

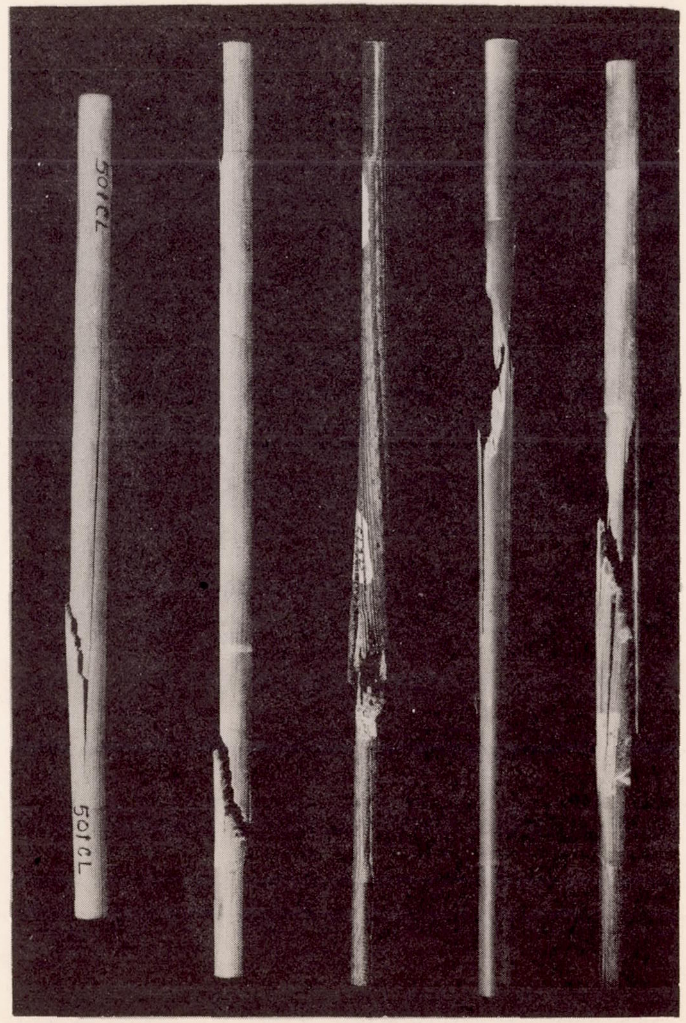


Figure 45.- Static torsion specimens showing type of fracture, round cross-sections; left to right, materials CL, C, R, P and G.

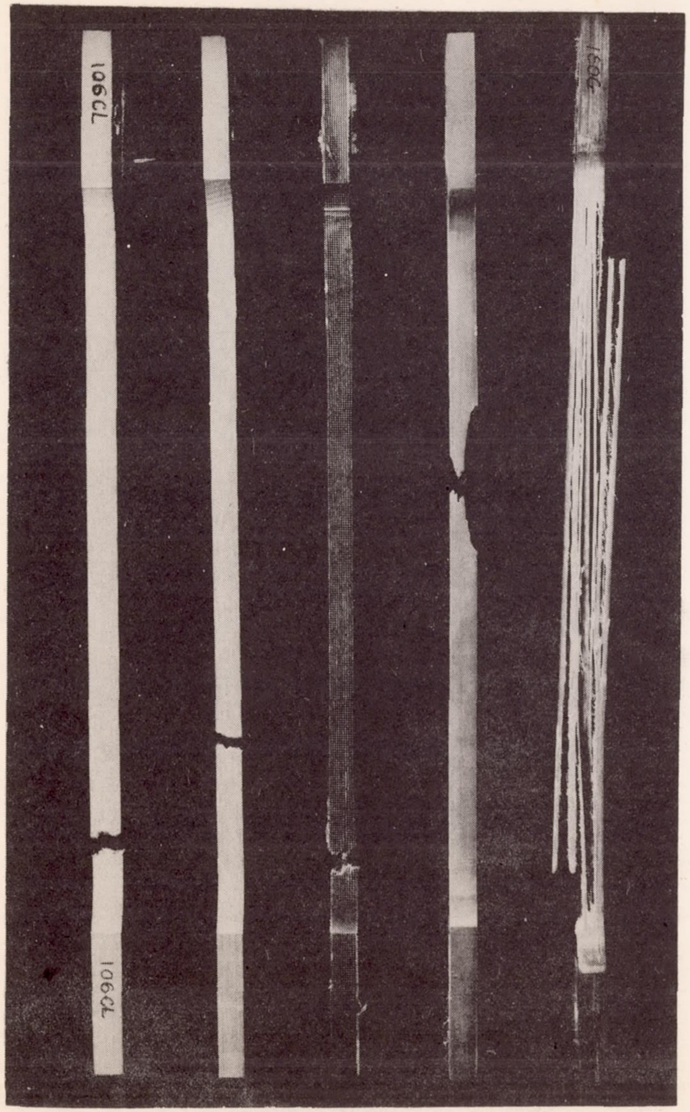


Figure 46.- Static tension creep specimens showing type of fracture; left to right, materials CL, C, R, P and G.

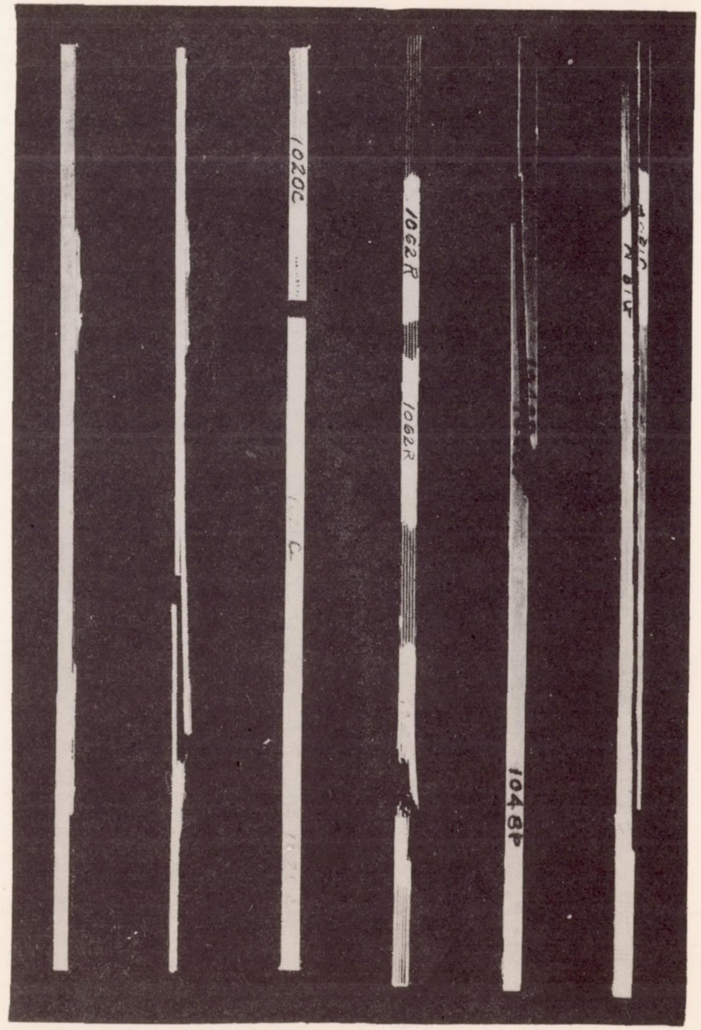


Figure 47.- Dynamic tension specimens showing type of fracture; left to right, materials CL, C, R, P and G

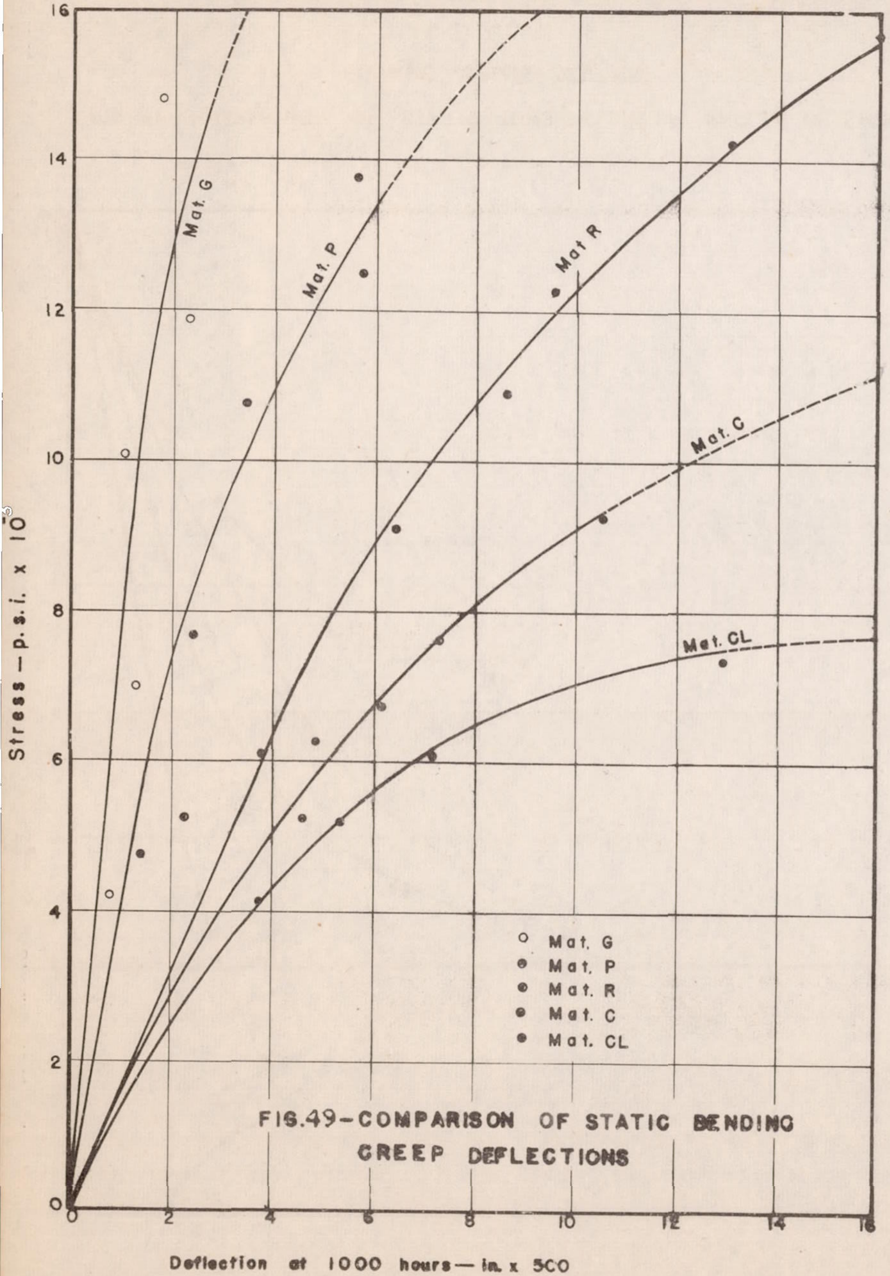


FIG.49—COMPARISON OF STATIC BENDING CREEP DEFLECTIONS

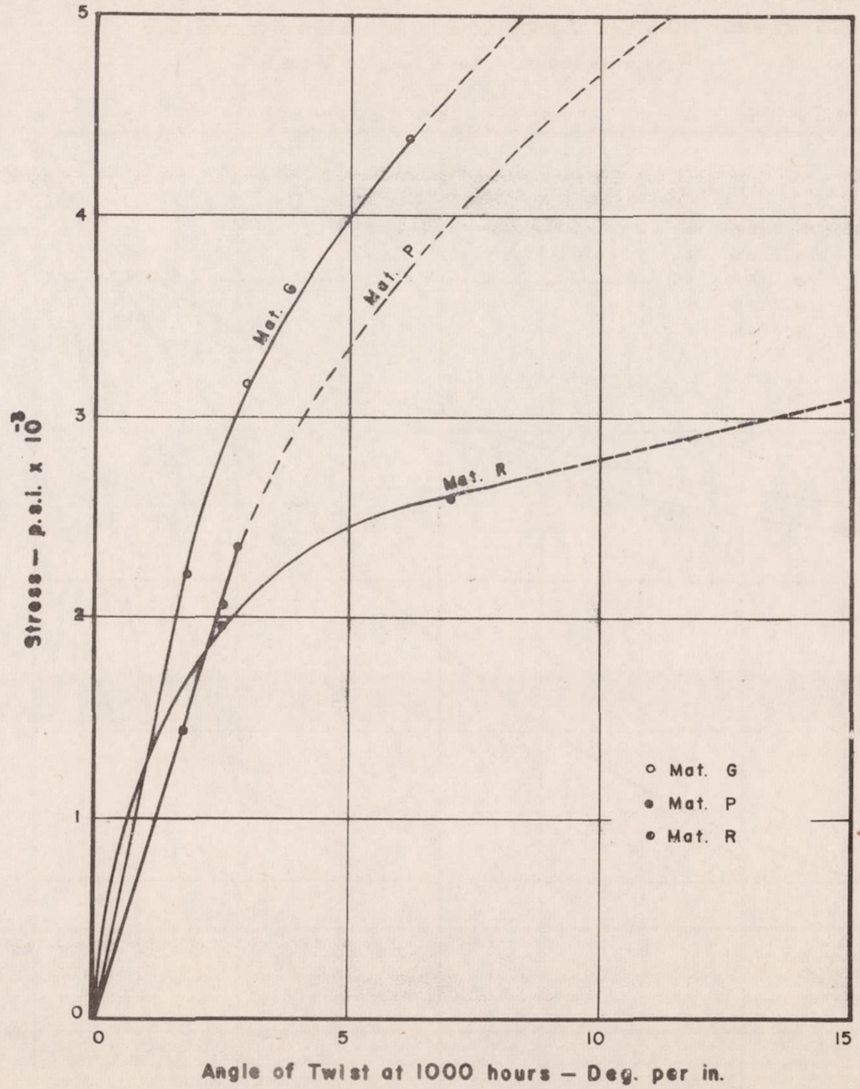


FIG. 50—COMPARISON OF STATIC TORSION CREEP ANGLES OF TWIST—ROUND CROSS-SECTION

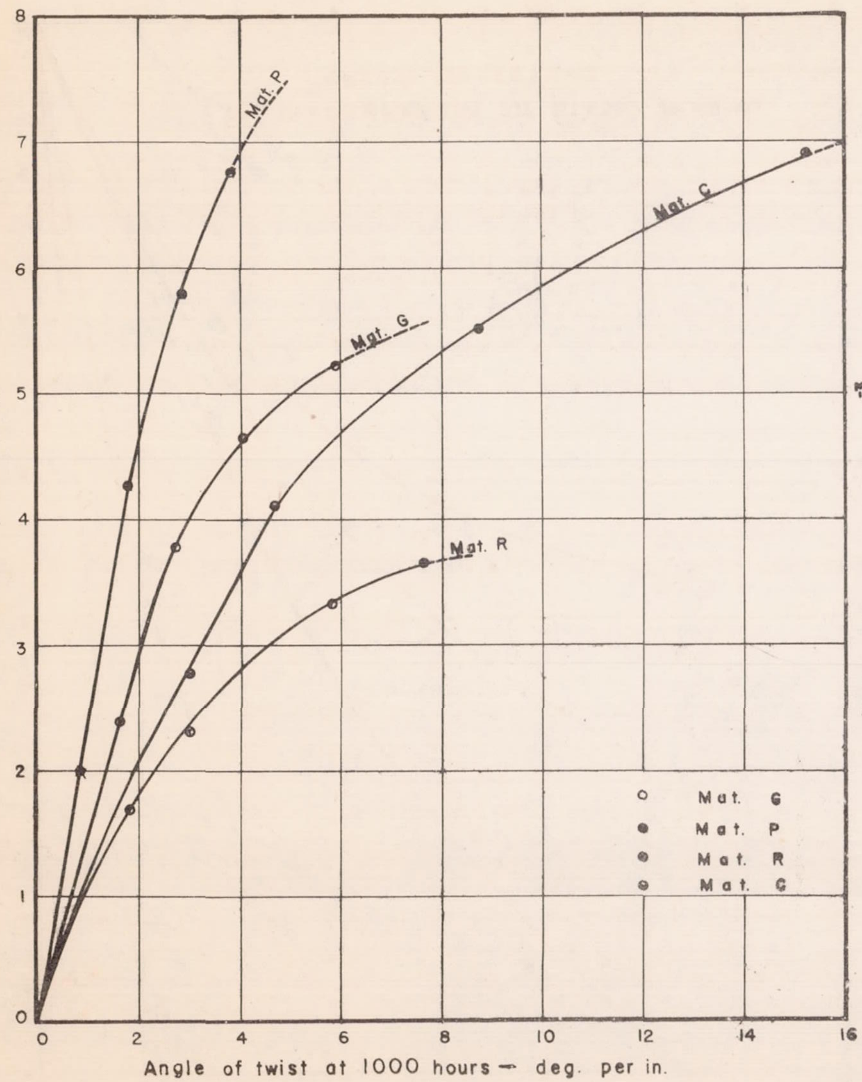


FIG. 51 - COMPARISON OF STATIC TORSION CREEP ANGLES OF TWIST SQUARE CROSS-SECTION

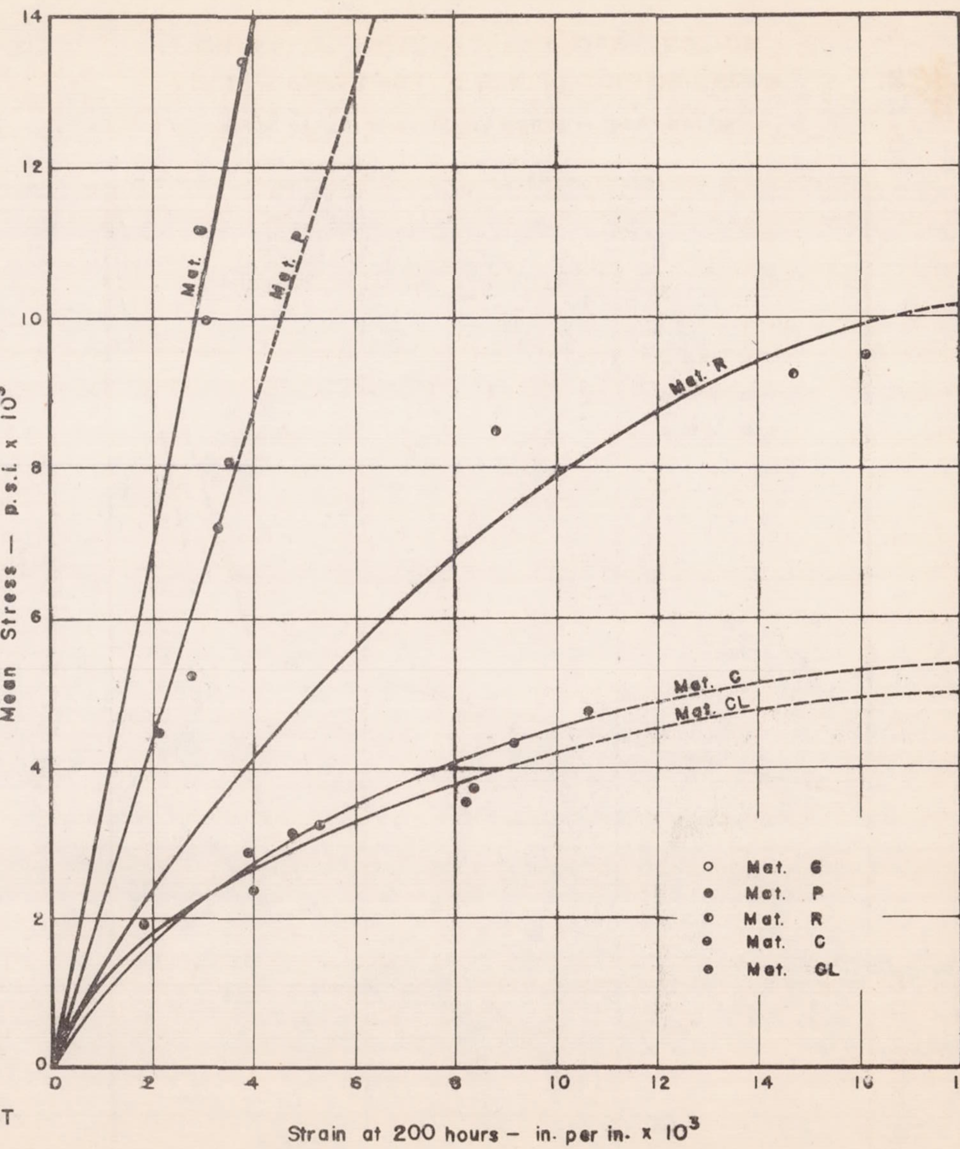


FIG. 52 - COMPARISON OF DYNAMIC TENSION CREEP STRAINS